Swarm Intelligence Based Adaptive Signal System

Jonathan Corey

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Reading Committee:

Yinhai Wang, Chair

Timothy Larson

Scott Rutherford

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Abstract

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Jonathan Corey

Chair of the Supervisory Committee:

Professor Yinhai Wang

Department of Civil and Environmental Engineering

With over 300,000 traffic signals in the United States, it is important to everyone that those traffic signals operate optimally. Unfortunately, according to the Institute of Transportation Engineers over 75% of traffic signal control systems are in need of retiming or upgrade. Agencies and practitioners responsible for these signals face significant budgeting and procedural challenges to maintain and upgrade their systems. Transportation professionals have traditionally lacked accessible and effective tools to identify when and where the greatest benefits may be generated through retiming and system feature selection. They have also lacked methods and tools to identify, select and defend choices of new traffic signal control systems.

This is especially true for adaptive traffic signal control systems which are generally more expensive and whose adaptive algorithms are proprietary, invalidating many traditional analysis methods.

To address these challenges, a new theoretical framework including queuing and traffic signal control models has been developed in this study to predict the impacts of signal control technology on a given corridor. This framework has been implemented in the STAR Lab Toolkit for Analysis of Traffic and Intersection Control Systems (STATICS) that uses an underlying queuing model interacting with simulated traffic signal control logic to develop traffic measures of effectiveness under different traffic signal control strategies and settings. The STATICS toolkit has been employed by the Oregon Department of Transportation and several other transportation agencies to analyze their corridors and select advanced traffic signal control systems. Furthermore, a new cost-effective adaptive traffic signal control system called the Swarm-Intelligence Based Adaptive Signal System (SIBASS) is proposed to address situations where optimum optimization strategies change with traffic conditions. Compared to the existing adaptive signal control systems, SIBASS carries an important advantage that makes it robust under communication difficulties. It operates at the individual intersection level in a flat hierarchy that does not use a central controller. Instead, each intersection self-assigns a role based on current traffic conditions and the current roles of neighboring intersections. Each role uses different optimization goals, allowing SIBASS to change intersection optimization criteria based on the current role chosen by that intersection. By designing cooperative features into SIBASS it is possible to create corridor coordination and optimization. This is accomplished using the characteristics of the swarm rather than external imposition to create order.

SIBASS is evaluated via simulation under varied traffic conditions. SIBASS consistently outperformed the existing systems tested in this study. On average, SIBASS reduced system average per vehicle delay by approximately 3.5 seconds and system average queue lengths by 20 feet in the tested scenarios. New approaches to tailoring traffic signal control optimization strategies to current traffic conditions and desired operational goals are enabled by SIBASS. Combined, STATICS and SIBASS offer a solid basis upon which to build future tools and methods to analyze traffic signal control systems. Future STATICS analytical modules may include estimating environmental performance and costs as well as improvements to pedestrian modeling and mobility analysis. Environmental and pedestrian considerations also present opportunities for improvement of SIBASS. New optimization roles can be created for SIBASS to address environmental and pedestrian optimization issues.

Acknowledgements

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One last acknowledgement goes out to the City of Bellevue, particularly Mike Whitaker and Mark Poch for their insight into traffic signal control and its associated factors. Many of the ideas presented here have been refined by their input and experience with traffic signals control and system transition.

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Chapter 1: Introduction

1.1 Background

One of the major challenges faced in transportation is congestion. With limited land for new roadways and increasing expense of construction, congestion is unlikely to be combatted through the building of sufficient new lane-miles of road to alleviate the basic problem of increasing vehicle traffic demand. Rural and urban travel demand has been growing for many years as may be seen in Figure 1-1 which shows United States Department of Transportation (USDOT) Federal Highway Administration (FHWA) travel volume trends (FHWA, 2008A) data overlaid with recession data from the Economic Research office of the Federal Reserve Bank of St. Louis (Economic Research Office, 2013). Combining increasing demand with only modestly increasing road lane miles, as seen in Figure 1-2, is a recipe for congestion before one even considers the impact of bottlenecks, induced demand or other network related operations and planning issues. Notice that Vehicle Miles Traveled (VMT) effectively doubled from 1980 to 2008, while total roadway miles showed only modest growth (with formerly rural roads becoming urbanized).

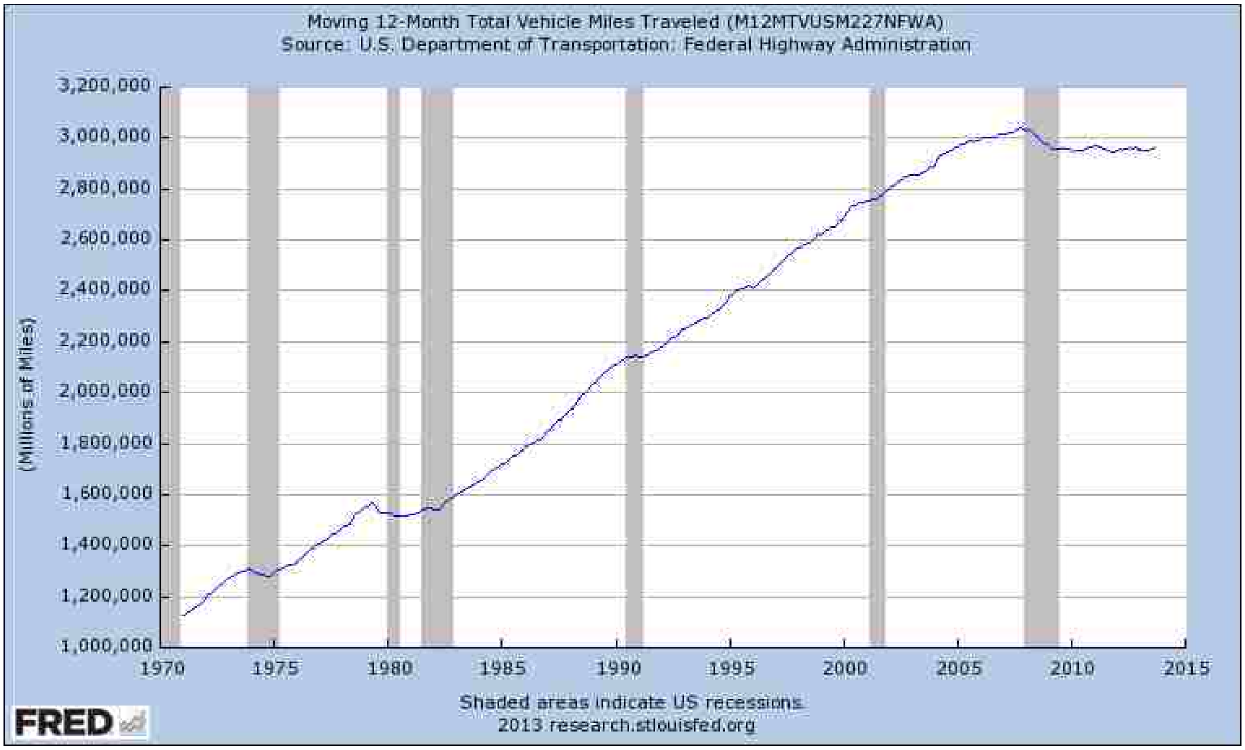


Figure 1-1: 12-Month Vehicle Miles Traveled (Economic Research Office, 2013)

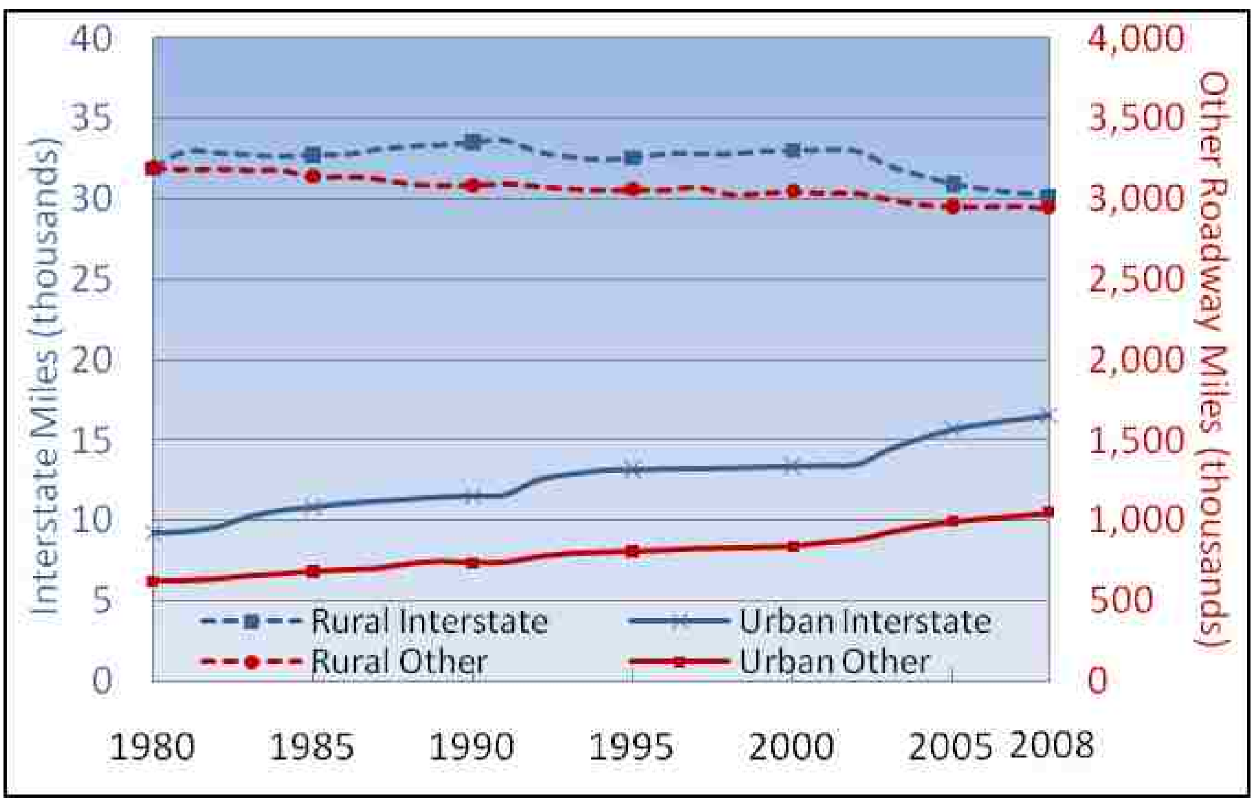


Figure 1-2: Public Road Miles (Figure 1-4 Our Nation's Highways: 2010 (FHWA, 2011))

When one considers the growth of urban development and population, the efficiency of roadway operation becomes vitally important. For the past 30 years urban VMT has been the majority of highway VMT and the fastest growing portion of VMT as seen in Figure 1-3. With high population density and dense networks, urban areas can experience highly complex operational interactions and have very high performance repercussions. Specifically, relatively small delays or inefficiencies are amplified by the number of people experiencing the problem and an urban system's lack of excess capacity to aid in dissipating queued traffic.

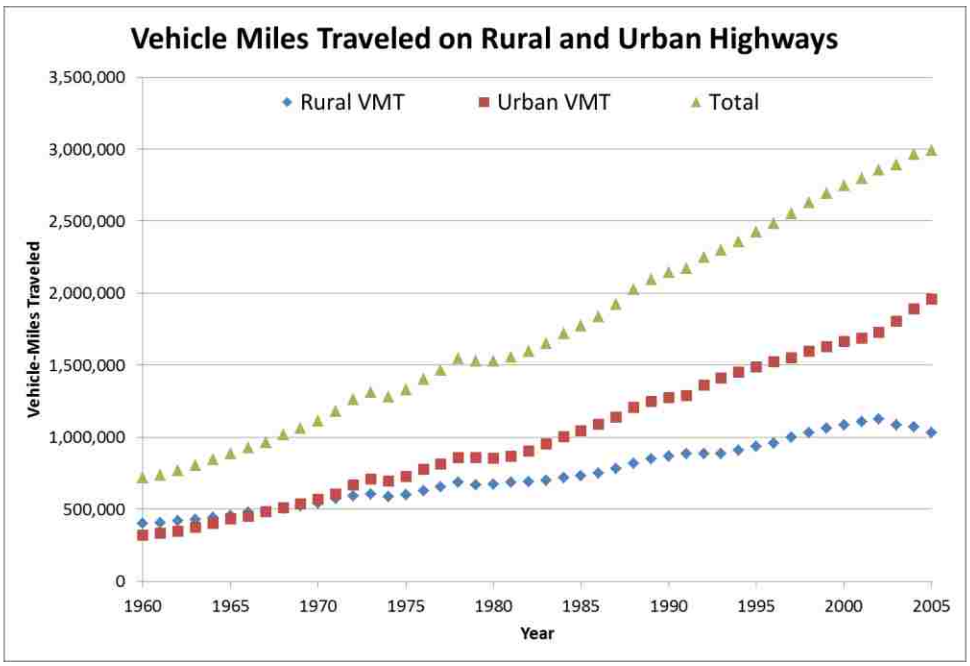


Figure 1-3: VMT on Rural and Urban Highways (FHWA, 2008A)

One area that needs specific attention is traffic signal control. The Institute of Transportation Engineers (ITE) estimates that there are approximately 300,000 traffic signals in the United States. The ITE also estimates over 75% of those signals could be improved by updating hardware or adjusting timing plans. The ITE reports that signal retiming can generate a 7-13%

reduction in travel time, a 15-37% reduction in delay and 6-9% reduction in fuel usage (ITE, 2014).

Likewise, the 2012 National Traffic Signal Report Card (NTSRC) (Figure 1-4) produced by the National Traffic Operations Coalition (NTOC) (2012) indicates that traffic signals are generally managed poorly, operated adequately, retimed adequately, subject to dismal monitoring and data collection, and maintained adequately. This is not high praise for the state of traffic signal control in this country. The traffic signal operations, signal timing practices and traffic monitoring and data collection sections of the 2012 NTSRC are the most important areas to focus research. The management and maintenance aspects of traffic signal control are largely functions of funding, leadership and resource management.

Figure 1-4: 2012 National Traffic Signal Report Card (NTOC, 2012)

Specifically, the 2012 NTSRC traffic signal operations section notes that agencies are only rarely updating signal and timing inventories to reflect field changes, traffic signal performance is not regularly measured according to stated operational objectives and timing plans are not in place for special events or emergencies. Under signal timing practices the 2012 NTSRC notes that signal timing practices tend not to be documented, timing plans fail to consider all available operational settings and timing plans may not meet all traffic demand patterns they would be expected to encounter. Traffic monitoring and data collection is particularly poorly executed according to the 2012 NTSRC with little real time traffic data and virtually non-existent traffic data quality control.

The 2012 NTSRC noted that current timing practices are frequently undocumented and frequently fail to consider all times of day, weekends and special events. Adaptive Traffic Signal Control (ATSC) offers a means to address these failures. Specifically, ATSC offers a means of providing traffic signal control parameters that are up to date and calculated consistently. Similarly, ATSC systems can adapt to unexpected traffic conditions, which allows ATSC systems to react to differences in traffic pattern across varied times and traffic conditions.

1.2 Survey of Traffic Engineers

In addition to the trends and practice challenges faced by signals engineers there are a number of additional operational challenges. A survey conducted for the Oregon Department of Transportation (ODOT) in 2011 collected responses from 55 transportation engineers. These engineers had an average of 15 years of experience with responsibility for an average of 950 signals. System sizes varied from 35 to over 6,000 signals. Responses were received from 25 cities, 15 counties and 15 states. Figure 1-5 shows the distribution of respondents' experience and Figure 1-6 the distribution of signal system sizes.

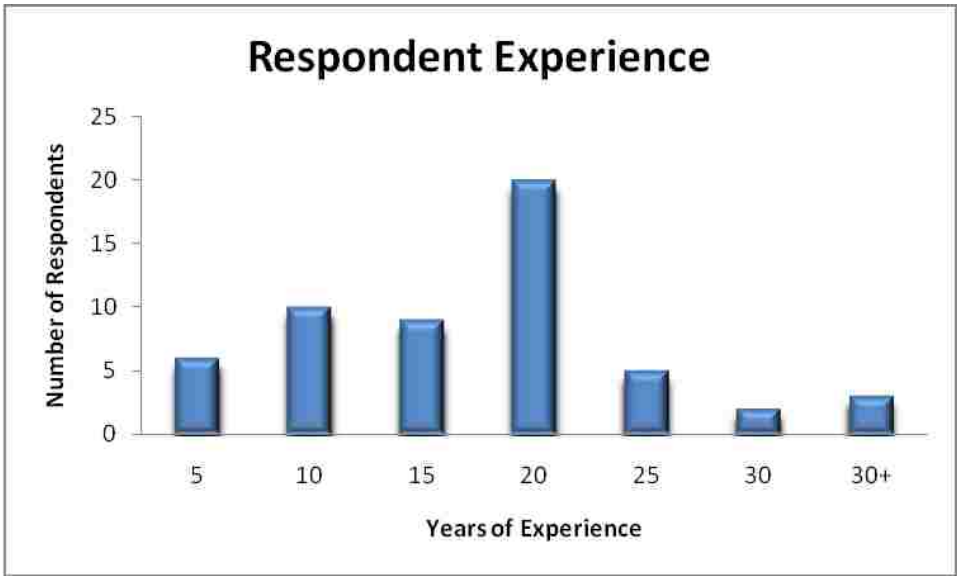


Figure 1-5: Experience level of respondents

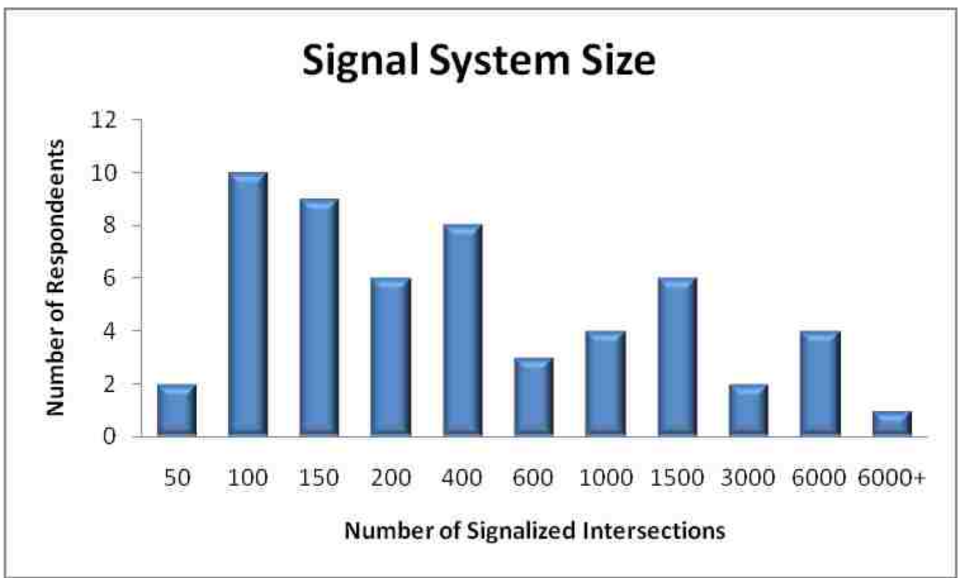


Figure 1-6: Size of signal systems administered by survey respondents

All signal engineers reported that they operated a majority or totality of their signals under conventional systems, i.e. actuated or fixed time control. Eleven reported they were currently operating some signals, typically from 5 to 15, under adaptive signal control systems such as

SCATS, SCOOT, InSync, etc. Another 4 were in the process of implementing adaptive systems in test implementations. The largest adaptive installations reported were in Plano, TX with over 100 signals operating under InSync and McKinney, TX and Bellevue, WA with 80 and 31 signals operating under the SCATS system. Out of the 52,400 signals represented by the survey respondents, less than 500 were operating under adaptive control.

The survey also asked respondents to identify the challenges they faced in practice. Table 1-1 shows how many respondents indicated they faced each particular problem. The primary challenge identified by respondents was detector malfunction with over 80% of respondents indicating it caused difficulties with signal operations. Signal coordination came in second with a majority of respondents indicating it was challenging for them to achieve. Saturated traffic, communications failures and variable traffic demand were problems for a plurality, if not majority of respondents.

Table 1-1: Challenges faced by respondents

Challenge	Frequency	Percentage
Detector malfunction	45	81.8%
Signal coordination	34	61.8%
Traffic saturation	27	49.1%
Field communications failure	25	45.5%
Variable traffic demand	23	41.8%
Pedestrian traffic	19	34.5%
Work zones	18	32.7%
Special events	12	21.8%
Emergency vehicle activity	11	20.0%
School traffic	11	20.0%
Controller programming	10	18.2%
Other:	10	18.2%
Weather	8	14.5%
Large vehicle effects	8	14.5%

These challenges have operational implications. Specifically, malfunctioning detectors blind or confuse intersection traffic signal controllers and limit their operational effectiveness. Coordinating traffic signals is difficult enough before taking other challenges into account. Saturated traffic conditions can lead to gridlock, preventing any traffic movement at all, not just for the congested movements. Communications failures can cause significant system disruptions, first by causing the cutoff signals to fall back to their backup control methodology and, after reacquiring communications, put the signal(s) into transition while matching plan, cycle, offset and phase order parameters to the system again. Finally, variability in traffic demand can cause a range of difficulties. Spikes of high or low demand will, at best, be cases where the current plan generates less than ideal performance. In more extreme or extended cases, traffic responsive systems may undesirably change plans, adding transition delay to the performance penalty caused by the demand spike. Transition is discussed further in the literature review.

1.3 Problem Statement

Ultimately there are two major problems facing traffic signal engineers. The first is how to pinpoint the problems using data observed and the second is what to do to fix the identified problems. Both problems are important for traffic operations deserve serious research to resolve due to its complexity as well as the amount of data and factors involved.

The development of a set of analytical tools, the STAR-Lab Toolkit of Analysis of Traffic and Intersection Control Systems (STATICS), for practitioners to use in analyzing and optimizing the operations of their signals is of great need and importance. Currently, practitioners lack a rigorous analytical approach to analyze their existing system operations and select replacement systems. An analytical approach is necessary because the number of features found in current systems and the plethora of potential replacement systems make evaluating even a meaningful fraction of them a significant undertaking. Also, while it is not a direct research concern, the politics of funding and traffic impacts on road users necessitate a documented approach with clear results indicating why a given result is recommended.

There are two solutions to traffic signal problems once signal re-timing options have been exhausted, employ advanced features embedded in the current signal control system or choose a new traffic signal control system. Advanced features, such as Left Turn Phase Reservice (LTPR) and Conditional Left Turn Phase Reservice (CLTPR) may offer solutions to specific traffic problems, however, practitioners often lack the tools and guidelines to identify the specific conditions where applying these features might be beneficial. Other operations options like choosing between checking gap-outs by phase group or by lane can also have an impact where disparities in lane usage exist. Determining whether to use these options with the current system or choose a new system to evaluate has traditionally been left to the judgment of signals engineers, who may or may not have sufficient knowledge, system oversight or understanding of their current and available systems to make an informed decision.

Addressing this lack of an analytical framework has been challenging for several reasons. First, practitioners, and their political or managerial superiors, need to be able to understand and evaluate the logic used in the analysis. Second, the tools need to be designed in such a way that they are available to practitioners at large. Simulation software and many of the primary traffic operations programs used in practice are not cheap and often operate as black boxes with limited public information about their assumptions and operating principles. An additional issue with such software is the steep learning curve associated with setting up tests and analyzing results. This can leave practitioners unable to answer critical questions about how conclusions are reached.

A third reason that analytical framework development has been challenging is the impact of random effects on traffic operations. While fixed time operations are not appreciably affected by changes in arrival patterns, actuated control, to a lesser extent, and adaptive control systems, to a greater extent, are affected by random arrival patterns. This causes an additional concern for system evaluations because the behavior can change based on specific arrival patterns. To address the issue of arrival pattern dependency, stochastic variation is introduced via the Monte Carlo Method (MCM) (Metropolis and Ulam, 1949), using multiple runs with different random number factors to create a range of possible outcomes from which average performance can be derived.

After the analysis has been completed, practitioners typically face a choice between keeping the existing system as is, enabling selected advanced settings and replacing the current system with a system whose operating principle best matches the signal's needs. To make these decisions, practitioners require performance estimates for the different configurations under consideration and a means to compare them. As a part of the analytical framework, common performance measures such as stops, delay and queues are gathered and then converted to monetary values to judge whether a new system or setting selection is justified.

For cases where no existing system is judged suitable, a new system capable of addressing gaps between known systems is required. Considering the longevity of traffic signal control systems, it is important that a proposed new system address as many current and foreseen future considerations as possible. First, the new system needs to address known deficiencies in current practice. Second, a new system should address obvious future concerns to the extent possible without compromising current operability. Finally, any new system should not be designed without considering past lessons learned regarding traffic signal control.

Engineers in practice need a system that addresses the concerns they face on a regular basis. They need a system that will be robust to failures of detectors and communications. In addition to being failure robust, the system needs to be free of transition related issues and reacquire coordination as quickly as possible with minimal performance impacts. Likewise traffic engineers need a system that adapts to current traffic conditions and can address variability in demand.

Another aspect of many current systems that limits performance is limited internal usage and external visibility of data. One method of achieving data visibility over the network is to instrument the network with many sensors and coordinate those sensors across the network to track individual vehicles from moment to moment. Unfortunately, the cost, operational and privacy concerns inherent to such a venture would be prohibitive. Connected vehicles offer this to some degree, as each vehicle can report its own position and desired route, but there are currently few, if any, vehicles with such systems on the road, much less available to the general public. Alternative methods for achieving data visibility include microsimulation and macroscopic models. Microsimulation modeling software such as VISSIM (PTV Vision, 2013) and TRANSYT-7F (McTrans, 2013) offer possibilities for real time network visibility, however the difficulty and expertise needed to setup and maintain such models with real world and real time data inputs are prohibitive for most uses and users. Similarly, macroscopic models relying on large spatial and temporal time scales are of limited use for low level activities such as traffic signal control.

Another important consideration for traffic modeling with regards to traffic signal control is the ability to model individual vehicles. This capability is necessary for several reasons. First, it allows for granular data collection and analysis by being able to aggregate desired data to the vehicle level, instead of just to the link and by time period. Second, by tracking individual vehicles a number of useful data sets can be collected, including estimated emissions and potentially enough data to generate approximate origin and destination pairs. Finally, by modeling at the individual vehicle level, this model should be able to accept input from connected vehicle systems as they enter the market.

As the 2012 NTSRC reported, there are several deficiencies in current practice. Data collection is currently the major area of deficiency. This is largely a communications infrastructure and software design problem as many intersections include detectors such as inductive loop detectors, radar and video image processors, the detector inputs are simply not communicated to traffic management centers. This can be due to any of a number of factors, such as insufficient communications infrastructure, antiquated hardware configuration and software/firmware limitations.

The current deficiency in data collection is one of the driving reasons for a real time model requirement. The real time model has several important implications for traffic signal control. With a model to base traffic signal control on, it is possible to predict vehicle arrivals at downstream intersections. Similarly, with historical data availability, it may be possible to predict the disposition of arriving vehicles amongst possible turning movements, allowing for additional efficiency in signal operation. Another important aspect of operating traffic signal control based on a model is that it allows for more robustness with regards to detector failure because inputs from other detectors in the system can be correlated with the data that would be provided by the malfunctioning detector.

1.4 Research Objectives

This research addresses traffic signal control operations in two steps. First, an evaluation methodology must be developed to identify and test potential performance enhancing features and replacement system characteristics. Second, if no current systems are suitable for implementations, an alternative system designed to address likely shortcomings will be designed.

Major research objectives of the analysis framework include:

- Develop analytical methods for intersection performance monitoring and analysis using operational, geometric, and traffic data readily available in practice
- Implement the analytical methods in Microsoft Excel to automate calculations and estimates
- Output common performance measurements for comparison in a cost-benefit analysis

Likewise, there are a number of major research objectives implicit to this development of an urban ATSC system.

- Develop a lightweight and modular and extensible model to underlie the ATSC
- Design detector and communications failure robustness into the system
- Ensure the system is capable of reporting data to support as many operation goal evaluations as possible

1.5 Study Scope

To accomplish the research objectives, a traffic signal control analysis toolkit to analyze the performance changes on a corridor given different systems and settings called the STAR Lab Toolkit for Analysis of Traffic and Intersection Control Systems (STATICS) is developed. STATICS is implemented in Microsoft Excel and incorporates a queuing based model to translate 15 minute interval data into low level data suitable for MCM analysis of fixed time, actuated and adaptive systems with selected advanced features. These results are then converted to monetary values to allow comparison across systems with different performance strengths and weaknesses.

Additionally, the proposed ATSC system begins with a focus on the development of a low complexity network model suitable for a range of devices and scales is designed, implemented, and tested. The proposed model is intended to be applicable to many different applications, beginning with ATSC. The ATSC system, named the Swarm Intelligence Based Adaptive Signal System (SIBASS), overlays the network model and is designed to optimize individual intersections. SIBASS is a distributed system that is intended to operate on as low of a level as possible while still providing improvements in data collection, intersection performance, and network performance. Finally, the model and SIBASS need to be operable with imperfect data. To achieve this, the detector layout will is designed to produce data redundancy within the model.

1.6 Dissertation Organization

The remainder of this work is divided as follows. A review of the current state of the art may be found in Chapter 2. The design and implementation of the traffic modeling supporting STATICS is detailed in Chapter 3. The control strategies and logics evaluated for and included in STATICS are covered in Chapter 4. The cost and benefit evaluation work that follows STATICS evaluation is described in Chapter 5. Chapter 6 covers the QACD model that was developed based upon experience with developing STATICS. Chapter 7 describes the control logic used in SIBASS. Chapter 8 shows the results of simulation testing. Chapter 9 gives an overview of the implementation process and Chapter 10 offer conclusions and concepts for future research.

Chapter 2: State of the Art

Before creating a new traffic model and ATSC system, it is important to review existing publications and take stock of the state of the art. Specifically, a review of previous work regarding traffic modeling, conventional systems, ATSC systems and operational challenges is warranted. The results of this literature review are presented below.

2.1 Traffic Modeling

Traffic modeling comes in many forms. Much of the early work focused on macroscopic modeling, specifically aspects of traffic such as routing and congestion. As time and technology progressed, interest in the interactions of traffic with traffic signals increased. Eventually technology progressed enough to apply computers to modeling traffic, which enabled more detailed modeling and simulation systems to be developed.

In order to cogently discuss macroscopic modeling, it is important to define the differences between macroscopic, microscopic and mesoscopic modeling. The simplest divisions are that macroscopic models rarely consider individual vehicles and focuses instead on the states of the system, such as vehicle average delay, expected queue lengths and so on. Microscopic modeling explicitly considers individual vehicles and their behaviors. Mesoscopic modeling lies in between macroscopic and microscopic modeling. Mesoscopic modeling typically considers individual vehicles only at a simplified level.

2.1.1 Macroscopic Modeling

Early macroscopic modeling and fundamental traffic flow theory developed concurrently from the 1930's through the 1960's. The development began with Adam's work considering the probability of a road being congested as a random series model (Adams, 1936). These developments were concurrent with work such as Greenshields' volume and speed models (Greenshields, 1935). As the state of the practice advanced, more approaches were developed, particularly relating to intersections. One new method proposed treating traffic as though it were a fluid and applying previously developed fluid flow theory methods to traffic flow (Pipes, 1953). Another traffic flow model to advance in the 1950's was the kinematic wave model (Lighthill and Witham, 1955; Richards, 1956) also called the LWR model.

Early macroscopic work tied closely to the earlier traffic flow theory work or used regression of observed data to generate a model. For example, to estimate central business district average speed, a number of different formulae were fitted to data from six English cities by Branston (1974). These formulae were selected from the then current work and include a power curve based on Wardrop's (1969) work on vehicle routing along with a more generalized form designed to prevent a prediction of zero speed at the city center, a linear regression by Breimborn (1970), a negative exponential equation based on Angel and Hymans (1970) work and a final function drawn from Lyman and Everall's (1971) work.

Many of the macroscopic models that have been developed more recently depend on fluid models, with work transitioning from the liquid based models used to develop traffic flow theory to gas based models. Whitham (1974), Payne (1971), Prigogine and Herman (1971) and Paveri-

Fontana (1975) developed the early gas based velocity models. As research progressed the question was how to treat vehicles that were close together. Specifically, the question was how to deal with the non-ideality of vehicles occupying non-trivial amounts of space while using gas equations that assumed point volumes. Continuing work by Helbing (1996) and Klar and Wegener (1997) added additional factors to compensate for vehicle-vehicle interactions. More recent work has added additional factors to the gas diffusion model to account for the synchronization inherent to congested traffic (Helbing, et al., 2001).

2.1.2 Mesoscopic Models

Mesoscopic models fall between macroscopic and microscopic models in the level of details they consider. Macroscopic models might judge the state of a link through aggregated volume, occupancy and speed. Microscopic models might consider numerous factors including individual vehicle acceleration parameters and driver behavior. Mesoscopic models compromise and consider a limited number of parameters at the individual vehicle or platoon level.

One common macroscopic model is the Cell-Transmission Model (CTM) developed by Daganzo (1994, 1995). The CTM breaks a link into a number of individual segments of arbitrary length. Cells in the CTM have three configurations, propagation, merging and diverging. Cells that propagate have linear connections that receive traffic from upstream and release traffic downstream. Merging cells accept two or more inputs from upstream cells. Diverging cells allow traffic to travel to one of several downstream cells.

The CTM has been used and adapted by several other researchers. Li (2011) used the CTM to optimize traffic signals. By adapting the cells to better fit the segments and configurations of an urban network, such as left turn bays, Li was able to include left turn bay overflow and occlusion in the analysis. Floetteroed and Nagel (2005) extended the CTM handling of intersections by creating a fourth cell type that generalized the merge and diverge functions into a single cell type intended for use as an intersection cell where multiple movements merge and diverge.

2.1.3 Microsimulation

Microscopic models, typically in the form of microsimulation programs, seek to emulate as many factors as possible related to traffic flow. Microsimulation software tracks individual vehicles and their current speeds, locations, following distance, lane change behavior and so on. Additional traits, such as simulated passenger counts, routing behavior and many other factors may be tracked as well. This makes microsimulation a very powerful tool for transportation analysis, but it also makes for steep learning curves and high barriers to entry in terms of cost, expertise and required data. Microsimulation models are also subject to garbage in, garbage out like any other computer program, making input data quality of significant concern.

There are a number of microsimulation programs and methodologies. Two programs are particularly important and relevant to this work. The first is VISSIM (PTV Group, 2013), the second is TRANSYT (Robertson, 1968). VISSIM is a microsimulation program developed by PTV Group. VISSIM includes the ability to control the simulation software via a Component Object Model (COM) programming interface (PTV, 2012). The VISSIM COM interface allows researchers to program in languages such as C++ and C# and control vehicles, traffic signals and other properties of the simulation. TRANSYT is a package of traffic modeling and optimization package. The TRANSYT system was originally developed in the United Kingdom. Eventually the United States FHWA became interested in the software and developed a branch of TRANSYT, TRANSYT-7F for use in the United States (McTrans, 2013).

2.2 Conventional Traffic Signal Control

Fixed time control and actuated control are two common signal control strategies among conventional traffic signal control systems. Fixed time control is widely used where traffic is predictable and consistent because it does not require the added complications and expense of traffic sensors. Actuated control is often implemented at isolated locations and where traffic is less predictable and requires field traffic detection to operate. Many controller firmwares have the capability of implementing either fixed time or actuated control without any additional software, though additional software is often used to administer such systems.

The W4IKS firmware produced by Wapiti Micro Systems and Northwest Signal Supply's Voyage firmware are two examples that can be used to implement basic signal control strategies. The W4IKS firmware operates on model 170 controllers (*Wapiti Micro Systems Corp, 2011*) while the Voyage firmware is designed for 2070 and NEMA controllers (*Northwest Signal Supply, Inc., 2008*).

W4IKS combines the computational engine required to operate the signal in fixed time or actuated modes with a user interface that allows engineers to input customized control parameters. While the W4IKS firmware is flexible, it is also constrained by the platform it is designed to operate on (*Wapiti Micro Systems Corp, 2011*). The model 170 controller has very limited memory and storage capacity. The model 170 specification was also not originally designed to accommodate communications. Native communication capabilities were added with the model 170E specification. While the W4IKS firmware has served well, the platform is obsolete and programming for the platform is more labor intensive than some other platforms. Transmission speeds and the ability to store and switch timing plans are also limited on the W4IKS firmware and the model 170 platform (*Wapiti Micro Systems Corp, 2011*).

The Voyage firmware is designed for the 2070(L) and NEMA (2070N, M1) platforms as described in the Voyage traffic controller software datasheet Version 1.6.0 (*Northwest Signal Supply, Inc., 2008*). ODOT is replacing 170/W4IKS implementations directly with 2070/Voyage as part of their system modernization. Voyage incorporates a user interface similar to that found in W4IKS. The 2070N and 2070 controller specifications used with Voyage offer dramatic improvements in memory, storage space, and communications. These improvements make the Voyage firmware more capable than model 170/W4IKS implementations.

Conventional systems, like fixed time and actuated control, require plans that include phase split, cycle length, offset and special feature usage data in order to operate. These plans are commonly selected either by time of day or using detectors in the system to look for specified traffic patterns. A conventional system's performance is defined by how well the plan in use is suited to the current traffic pattern.

2.3 Adaptive Traffic Signal Control

As the goal of this work is to develop an ATSC system, it is important to review existing ATSC systems. The system optimization and operating principles of currently available ATSC systems are of particular interest. Agent based systems, which are currently under development, are also reviewed here as they are conceptually the closest ATSC system to SIBASS.

2.3.1 SCATS

The Sydney Coordinated Adaptive Traffic System (SCATS) was developed in the 1970's by Roads and Maritime Services (formerly the Roads and Traffic Authority) of New South Wales, Australia (2013). SCATS was originally developed for implementation in Sydney, Australia, where traffic congestion was a major issue. SCATS has a two level optimization paradigm, strategic and tactical. Strategic optimization controls whether individual intersections and groups of intersections coordinate. SCATS coordinates (marries) intersections and groups of intersections based on volumes traveling between intersections. Tactical optimization determines the allocation of green time between movements at each intersection. Tactical optimization is based on the degree of saturation, a measure of the time a sensor is not occupied, which correlates to the distance between vehicles in motion (Lowrie, 1992).

Experience with SCATS has shown it to produce data useful to engineers, but with some troublesome limitations. Specifically, the real time availability of data allows engineers to understand and react to current conditions in a timely manner. However, many of the most useful pieces of information are either discarded or aggregated to less than useful time intervals. For example, individual detector actuations are reported to the central control system on an individual detector basis; however, the output files only contain volume and degree of saturation values at the five minute and stage aggregation levels.

2.3.2 OPAC

Optimized Policies for Adaptive Control (OPAC) is a product of the FHWA's focus on Intelligent Transportation Systems (ITS) development in the 1980's. OPAC is a distributed system designed to minimize delay and stops at the local level and achieve coordination via a virtual cycle modified by real time data. The OPAC system seeks to pick the best time to transition from serving one phase to the next to minimize delay and stops (Gartner, Pooran and Andrews, 2001).

2.3.3 SCOOT

The Split Cycle and Offset Optimization Technique (SCOOT) was developed by the Transport and Road Research Laboratory of the United Kingdom in the late 1970's and early 1980's (Hunt, et al., 1982). The SCOOT system uses exit detectors at upstream intersections to predict arriving traffic a short time into the future so that splits, cycle lengths and offsets can be optimized. The SCOOT system optimizes on a small time threshold where the system chooses whether the current phase should be terminated, executed as planned or extended a short time. The SCOOT system bases its optimization on modeled queues (Robertson and Bretherton, 1991).

2.3.4 Agent Based ATSC

Agent-based ATSC systems have been one of the newest areas of research into ATSC. Agent based methods use simple logical choice algorithms to represent the actions of a given aspect of the system. For example, an agent representing a driver on the network might be designed to pick routes with minimal complexity and length, such as selecting the route with the least distance on surface streets and fewest turns. Several agent-based methods have been proposed. These methods tend to vary in the number and hierarchy of agents and what optimization criteria are used. Much of the agent-based work has come for the vehicle routing and advanced traveler information systems aspects of ITS research.

One agent-based method developed by Adler, et al. (2005) (Adler and McNally, 1994; Blue et al., 1997; Adler and Blue, 1998) uses a series of agents to manage individual vehicle routing, local traffic signal control and network vehicle routing allocation. In this system, a vehicle on the network receives network information and an agent controlling the vehicle selects a route to travel upon. A signal control agent receives data from multiple vehicles and sensors and optimizes the traffic signal control system for those conditions. Finally, a network agent receives data from various signals and processes link status information to send to vehicle agents for route selection.

Another agent-based system was developed by Choy, et al. (2003). This hierarchical model was developed using fuzzy logic as the basis for decision making and multiple levels of agents to generate cooperative behavior. In this model, the low level agents have their fuzzy logic parameters adjusted by upper level agents. The system uses an online reinforcement system to keep the fuzzy logic parameters current with traffic and state conditions. Upper level agents choose how online reinforcement learning will adjust the fuzzy logic parameters. For example, a high level agent identifies congestion occurring on a corridor, it then changes the reinforcement process to favor results that reduce congestion, as opposed to delay or stops or other parameters.

2.3.5 ACS Lite

A relatively common signal system design is the closed loop systems. A closed loop system is where a number of traffic signals are linked together to a local master controller. This design is frequently used on corridors, where it may not have been practical to install communications back to a central traffic management center. The master controller in a closed loop system dictates when the subordinate controllers will change plans, either in a traffic responsive manner or using a schedule of timing plans (FHWA, 2005).

ACS Lite is an ATSC designed to operate on existing closed loop systems. It uses a library of timing plans as a basis for adaptive operations. ACS Lite adjusts the green time splits used at a traffic signal every 3-5 cycles. The ACS Lite system tracks saturation and redistributes time from the least congested to the most congested (Gettman, 2006).

2.3.6 InSync

The InSync system has been designed to abandon the traditional cycle where each phase is served in the same order every time. Instead, InSync is designed to dynamically generate green bands to progress vehicles along the corridor to minimize stops and delay. InSync serves movements outside of the greenband based on which movements have suffered the most delay (Rhythm Engineering, 2013).

2.4 ATSC Comparison Studies

Many states in the U.S. have begun to install advanced traffic control systems to upgrade their conventional signal systems. Often this means an advanced traffic signal control system replaces a conventional central or closed loop control system. Reports covering these upgrades, correspondingly, tend to have data for only two systems, the original, conventional system and the new, advanced system. This limitation means that a number of reports are required to show the performance improvements that are possible using advanced signal control systems, a minimum of one report per system. Over the remainder of this section, the results of several case studies will be presented in order to give readers as accurate a picture of system performance as possible.

The comparison case studies presented here generally use differences in performance measures such as corridor travel time and number of stops. Both of these performance measures are very dependent on the quality of timing plans in use by the previous system in the comparison, i.e., a bad plan will cause excessive travel time and a correspondingly high number of stops. Unfortunately, comparisons are complicated by the fact that agencies generally do not expend the resources to retime their intersections prior to changing their signal control systems. Because the author has no control over the conditions of the comparison, readers should note that improvement percentages are dependent on the quality of the pre-existing timing plans, parameters and alignments in use before the signal systems upgrade. When incorrect plans, parameters and alignments are in use before the evaluation, the before and after evaluation performance improvements can be inflated. The NCHRP synthesis report (Stevanovic, 2010) indicated that when a well-maintained and timed conventional system is replaced by an adaptive system, it can be difficult to achieve performance improvements with adaptive systems greater than ten to fifteen percent in any given performance measure.

2.4.1 SCATS

Beginning in 1992, Oakland County in the State of Michigan began converting their pre-timed coordinated traffic signal control systems to SCATS. There were 28 intersections in the test implementation. The sample data used to evaluate the project result was from a four-mile segment of M-59 from Pontiac Lake Road West to Pontiac Lake Road East consisting of seven signalized intersections. Table 2-1 shows the performance improvements seen on the study segment. Specifically, SCATS decreased the travel time by 6.7%, number of stops by 26.5%, queue length by 17.5%, total travel delay by 19%, fuel consumption by 5.1%, and increased the average travel speed by 7.0% (*Dutta and McAvoy, 2010*).

Table 2-1: Combined EB/WB weekday peak hour MOE comparison before/after SCATS in Oakland County, Michigan

Measure Of Effectiveness	Before	After	Change
Travel time (sec)	442.67	413.10	-6.68%
Travel speed (mph)	32.51	34.77	6.95%
Fuel consumption (gallons)	0.2269	0.2154	-5.07%
Number of stops	3.33	2.45	-26.43%
Total travel delay (sec)	158.04	127.93	-19.05%
Number of stopped vehicles	1289.96	1072.33	-16.87%
Maximum queue length	23.23	19.17	-17.48%

Source: *Martin and Stevanovic 2008*

The traffic signal control project in Park City, Utah changed the traditional TOD system to a SCATS system in 2005. All evaluations were from the 14 intersection signals along the corridor, and were collected between 7 and 9 AM (morning peak), and 4 and 6 PM (afternoon peak) on all weekdays, and noon and 2 PM (midday peak) on weekends under fair weather and dry pavement conditions. In general, the SCATS deployment in Park City, Utah has improved traffic operations. As shown in Table 2-2, the average travel time decreased by 5.8%, number of stops by 8.5%, and total travel delay by 15.5%. The travel times and delays on the major routes in the Park City network are always shorter with SCATS control than with the original TOD plans.

Table 2-2: MOE comparison before/after SCATS in Park City

MOE		AM NB	AM SB	PM NB	PM SB
Travel Time(seconds)	Before	907.3	895.8	888.0	951.3
	After	839.3	825.9	854.3	912.6
	Change	-7.5%	-7.8%	-3.8%	-4.1%
	Average change	-5.8%			
Stops	Before	7.8	7.2	6.0	8.5
	After	6.3	6.0	6.3	8.2
	Change	-19%	-16.7%	5%	-3.5%
	Average change	-8.5%			
Total Delay(seconds)	Before	335.0	307.4	305.4	375.5
	After	266.6	254.2	268.9	329.7
	Change	-20.4%	-17.3%	-12%	-12.2%
	Average change	-15.5%			

In March 2007, Gresham, Oregon changed their TOD plan system to SCATS at 11 intersections on Burnside Road. The study segment of four intersections along a 1.88-mile segment of Burnside Road showed an average reduction in travel time of 10.8% as shown in Table 2-3, although travel time increased in morning peak hours for the westbound direction (*Peters et al., 2007; Fehon and Peters, 2010*). In addition to the Gresham project, there are several other advanced traffic signal systems, including Voyage with advanced features and SCATS, deployed in Oregon under the ODOT Innovation Grant Program.

Table 2-3: Travel time comparison before/after SCATS in Gresham

Travel time (sec)		**Before**	**After**	**Change**	**Average Change**
East bound	8-10 a.m.	305	263	-19%	-10.8%
	12-2 p.m.	315	265	-16%	
	4-6 p.m.	373	314	-16%	
West bound	8-10 a.m.	226	248	10%	
	12-2 p.m.	321	294	-8%	
	4-6 p.m.	361	305	-16%	

By the end of 2010, there were 14 deployments of SCATS in the U.S. ranging from deployments of 11 signals up to 625 signals. SCATS has been installed in Oakland County, Michigan; Bellevue, Washington; Sunnyvale, California among others. There are also large installations consisting of thousands of signals in Sydney, Shanghai, and Hong Kong.

The SCATS system has been adding new features over time. Flashing yellow arrow, which allows permitted left turns after yielding to pedestrians and other cars, is one of the more recent additions. The use of the flashing yellow arrow has reduced the left-turn delay from 38 seconds per vehicle to 16 seconds per vehicle on Factoria Boulevard in Bellevue, WA. Note that this delay reduction is in addition to the savings already realized by changing to SCATS.

2.4.2 InSync

Three of the current InSync deployments have been evaluated to determine their net impact on traffic operations within their respective corridors. Hutton et al. (*2010*) evaluated the replacement of an actuated system with the InSync system and the evaluation results are summarized in

Tables 2-4 through 2-6. In Lee`s Summit, Missouri, a 2.5 mile long corridor including 12-signalized intersections showed decreases in stops as shown in Table 2-4. The average stop reduction reached 95% under some conditions. Total corridor delay decreased by 87%. Travel time, shown in Table 2-5, decreased by 18.8% (10.1% for northbound and 27.5% for southbound), which correlates with reductions in fuel consumption (*Hutton, et al., 2010; Siromaskul and Selinger, 2010*). Speed improvements are reported in Table 2-6.

Table 2-4: Number of stops along the corridor comparison before/after InSync in Lee`s Summit

Direction		AM Peak	AM off peak	Noon peak	PM Peak	Night
NB	Before	0.6	0.8	1.8	1.5	1.6
	After	0.7	0.4	0.6	0.7	0.3
	Change	17%	-50%	-69%	-57%	-81%
	Average Change	-48%				
SB	Before	3.9	4.6	4.7	2.6	1.8
	After	0.2	0.3	0.6	1.2	1.3
	Change	-95%	-95%	-88%	-56%	-31%
	Average Change	-73%				

Table 2-5: Travel time comparison before/after InSync in Lee`s Summit

Direction		AM Peak	AM off peak	Noon peak	PM Peak	Night
NB	Before	246 sec	247 sec	306 sec	292 sec	244 sec
	After	250 sec	234 sec	251 sec	248 sec	210 sec
	Change	1.6%	-5.3%	-18.0%	-15.1%	-13.9%
	Average Change	-10.1%				
SB	Before	343 sec	370 sec	392 sec	344 sec	251 sec
	After	233 sec	226 sec	245 sec	270 sec	232 sec
	Change	-32.1%	-38.9%	-37.5%	-21.5%	-7.6%
	Average Change	-27.5%				

Table 2-6: Travel speed (MPH) comparison before/after InSync in Lee`s Summit

Direction		AM Peak	AM off peak	Noon peak	PM Peak	Night
NB	Before	37.6	37.5	30.4	32.2	38
	After	37.4	39.8	37.4	37.5	44.1
	Change	-0.4%	6.0%	23.2%	16.5%	15.9%
	Average Change	12.2%				
SB	Before	27.3	25.5	23.8	27.3	36.9
	After	39.8	41.0	38.3	34.8	40
	Change	45.8%	61%	60.9%	27.3%	8.4%
	Average Change	40.7%				

Note that the magnitude of the improvements seen in the previous tables far exceeds the 15% percent that would be expected according to Stevanovic (2010), particularly for southbound travel. The southbound improvement may be conflated with improved coordination for that travel direction. Southbound coordination improvement may be indicated by the asymmetric improvement in number of stops in Table 2-4, travel times in Table 2-5 and travel speed in Table 2-6 to more closely match northbound traffic.

2.4.3 ACS Lite

In June 2009, Fulton County, Georgia changed eight intersections to the ACS-Lite system. The study data was collected at five adjacent intersections, from Fairburn Rd to I-285 on Cascade Road. Travel times, shown in Table 2-7, decreased by 15% and maximum queue length, shown in Table 2-8, decreased by 19.8% (*Wang, et al., 2010*). The results indicate that the ACS-Lite system effectively reduced the travel time on the arterial while simultaneously reducing queue lengths on side streets during peak periods.

Table 2-7: Travel time comparison before/after ACS-Lite in Fulton County

MorningPeak			
	Before	**After**	**Change**
EB: Fairburn to I-285 NB	67 sec	46 sec	-32%
WB: I-285 NB to Fairburn	122 sec	103 sec	-16%
EveningPeak			
	Before	**After**	**Change**
EB: Fairburn to I-285 NB	159 sec	136 sec	-14%
WB: I-285 NB to Fairburn	146 sec	136sec	-6%
Average of Both Peaks			
	Before	**After**	**Change**
EB: Fairburn to I-285 NB	113 sec	91 sec	-19%
WB: I-285 NB to Fairburn	134 sec	119 sec	-11%
Total travel time reduction	123 sec	105 sec	-15%

Table 2-8: Queue length comparison before/after ACS-Lite in Fulton County

MorningPeak			
Intersection	**Before**	**After**	**Change**
I-285NB	13.3	10.4	-21.8%
I-285SB	14.4	7.6	-47.2%
Utoy	14.9	11.3	-24.2%
Publix	2.4	2.5	0.4%
Fairburn	19.3	20.1	0.4%
EveningPeak			
Intersection	**Before**	**After**	**Change**
I-285NB	13.2	10.7	-18.9%
I-285SB	26.8	21.4	-20.1%
Utoy	17.2	17.3	0.05%
Publix	9.2	8.6	-6.5%
Fairburn	30.3	25.4	-16.2%
	Before	**After**	**Change**
Average of Both Peaks	16.1	13.5	-19.8%

The ACS-Lite installation in Gahanna, Ohio was implemented on Econolite NEMA hardware controllers and studied as a test bed. The improvements were then converted to a monetary savings using an hourly rate of $12.10 as a value of time for delay cost estimates and $2.25 as the per gallon price of gasoline. The ACS-Lite system was found to bring $88,500 in annual benefits from fuel savings and time savings at Gahanna, Ohio (Gettman et al., 2006).The ACS-

Lite implementation in Houston, Texas was implemented on Eagle controllers and evaluated with the same time value and fuel costs. The resulting annual benefits were estimated to be $577,648 (Gettman et al., 2006).

2.5 Oregon Adaptive Signal Control Experience

The STATICS evaluation toolkit described in Chapters 3 and 4 was developed on behalf of the Oregon Department of Transportation (ODOT). ODOT desired a means to determine when an adaptive system might be warranted and which system(s) should be more closely examined. This work was conducted while initial ODOT adaptive signal control systems were undergoing their initial performance evaluations. The following subsections detail selected installation reviews of ODOT adaptive installations.

2.5.1 InSync

The Oregon DOT installed InSync on a 1.7 mile section of Cornell Road from Butler Street to NE 48th Avenue in Hillsboro, OR as one of a number of adaptive signal control test installations. Hathaway, et al. (2012a) performed an evaluation of the new installation. Prior to the installation of InSync, the existing time of day system was retimed to enable a fair comparison of the existing system and the InSync installation.

The evaluation found that corridor travel times improved in both directions during the AM peak period and the midday off peak period. The PM peak period showed significant eastbound improvement (49 second reduction) with a very small reduction (3 seconds) in westbound travel time.

One caveat noted for the travel time measurements is that eastbound delay measurement may have been impacted by the sampling location which did not capture delay incurred while waiting for the eastbound tunnel. The authors noted that eastbound delay was likely overestimated by 5 to 10 seconds. Delay at three sampled intersections increased slightly overall. Overall, the InSync system represented an improvement in operations over the existing time of day system.

2.5.2 SCATS

As an additional component of the Oregon DOT's adaptive signal control systems testing two SCATS installations were implemented, one on the Tualatin-Sherwood Road and the other on US 97 and OR 126 at Bend, OR and Redmond, OR. The Tualatin-Sherwood Road installation begins at Teton Avenue and terminates at I-5. The US 97 installation stretches from Bend, OR (2 isolated intersections) to Redmond, OR (4 Intersections). The OR 126 installation is co-located with the US 97 installation in Redmond, OR. The OR 126 installation consists of a pair of intersections on a couplet of one way streets that intersects US 97 and two additional intersections beyond the one way couplet. The sites, Tualatin-Sherwood Road and US 97/OR 126, were last retimed in 2010 and 2008, respectively.

The Tualatin-Sherwood Road corridor serves a commercial area off of I-5 including businesses such as Costco and Kmart. Hathaway and Urbanik (2012) found that travel times decreased by approximately ten seconds for both east and west bound traffic in the AM peak, approximately 30 seconds each direction in the non-peak, and by 23 seconds for westbound traffic and 50 seconds for eastbound traffic in the PM peak. Total intersection average delay for selected intersections changed less than ten seconds, except for a 29 second average delay reduction at Martinazzi Avenue.

The analysis of SCATS operations on the Tualatin-Sherwood Road revealed a number of important trends. First, SCATS ran at generally higher cycle lengths than the preceding time of day system. Second, SCATS preferentially served the mainline over side street movements, increasing delay for side street movements and reducing the level of service ratings from D to E for some movements during the AM peak period. Third, SCATS made improvements in mainline progression through its adjustments of offsets. Some of the improvements were quite remarkable with reductions in mainline phase failures from over 40 per hour to fewer than 10.

Additional lessons were learned regarding the Teton Avenue intersection, which generally operated independent of the main corridor. Because of the proximity of a UPS distribution center, a high minimum green time was set to prevent gapping out of the side street phase when trucks were present. During other times, this resulted in unnecessary time allocation that reduced efficiency at the intersection. After the analysis, Washington County staff adjusted the system to use advance detection to address truck traffic issues. Overall, Hathaway and Urbanik (2012) found that SCATS is most appropriately applied to high volume corridors, based on their analysis of which intersections saw improvements in operations.

The evaluation for the Bend and Redmond SCATS installations Hathaway, et al. (2012b) was a little different from other evaluations in that it included an analysis of traffic during the Deschutes County Fair. This evaluation looked at the AM off peak period, midday period, PM peak period and the Deschutes County Fair. During the AM off peak period SCATS slightly increased travel times, 4% westbound and 2% eastbound, along OR 126, but also significantly reduced the cycle length from 80 seconds to 40 seconds. During the midday period SCATS resulted in minor improvements (3%-6%) in corridor travel times, but did so by reallocating cycle failures from mainline movements to side streets. PM peak period improvements to travel time were more significant with westbound OR 126 experiencing a less than 1% increase in travel time versus decreases of 6-9% for the other travel times.

Operations during the Deschutes County Fair are perhaps the most interesting. The travel times on US 97 decreased by 13% on NB US 97, 14% on SB US 97, 5% on WB OR 126 and 9% for EB OR 126.

Overall, Hathaway, et al. (2012b) found that the SCATS system allocates more time to the mainline, potentially at the expense of side streets. They also commented on the significant upfront costs in financial terms and staff time. Other observations by the research team indicated that having engineering staff in charge of the SCATS servers rather than IT is advantageous and that working with the vendor staff (TransCore) during setup makes maintenance easier in the long run.

2.5.3 General Observations

All three of the test installations resulted in per intersection costs near $50,000. Each evaluation also made particular note of detector quality being important to the success of the system. The various corridors seem to see average improvements on the order of 5-10% with peak improvements of approximately 12-14%. Both SCATS and InSync trade increases in side street and minor movement delay for mainline performance.

2.6 Operational Challenges

As noted in the survey, detector malfunction is one of the primary challenges facing traffic signal engineers. Without operational and accurate detection, traffic signals will not operate efficiently. Detecting detector error is a mature subject area for freeways and highways where work such as that by Chen and May (1987) and extensions by May, et al. (2004) have thoroughly documented the most common error types and ways to identify them. Common loop detector errors include chatter, cross talk and stuck loops among others. Chatter is when a loop detector rapidly cycles off and on. Cross talk occurs when traffic over one loop is detected by one or more loop detectors. Stuck loops stay on or off for extended periods. Each error has an establish means of detection for freeway operations. Many of the methods can and have been translated to traffic signal operations, but they need to be integrated at the operational level to work. Using stuck detectors as an example, it is relatively easy to demonstrate that a detector can remain occupied for a substantial period of time during a red light, a condition that would be decidedly abnormal during freeway operations. However, by modifying the error detection algorithm to be active only during green lights, when traffic is moving, many of the algorithms still work.

Transition is one of the major performance limits for conventional systems. Transition is defined by Shelby, et al. (2006) as "Transition is a period (or mode of operation) in which signal timing is modified to achieve coordination." There are a number of methods of achieving transition from one plan to the next. As an example, consider a transition from plan A to plan B where the only parameter to change is the offset increases for plan B. There are three ways to get the plans aligned, hold the current phase from plan A until it matches Plan B and run from there, add additional green time each cycle until the transitional cycle matches plan B, and subtract green time each cycle until the transitional cycle matches plan B. Different systems use different combinations and implementations of these basic methods. Typically, the addition and subtraction methods are limited to a fixed number of seconds or a fixed percentage of the cycle length depending on system settings (Shelby, et al., 2006). For small changes in timing plans transition may be as little as one cycle. Larger changes can run several cycles. At longer cycle lengths, transition may take as long as 10-15 minutes. During transition the timing plan experienced by traffic may vary considerably from the engineered plan intended by the traffic engineer. Because of transition it is uncommon for actuated or fixed time systems to have more than 3-5 plans. When more plans are used, the transition between plans occurs more frequently and generally negates the benefits that may be gained from more frequent plan changes.

2.7 Comparative Strengths and Weaknesses

In order to compare the overall characteristics of advanced traffic control systems such as ACS-Lite, InSync, and SCATS, surveys focusing on cost, maintenance, and reliability were conducted in 2009 and 2010 to compare the widely used adaptive signal control systems (Selinger and Schmidt, 2010). The objective of the surveys was to identify a short list of the technologies that practitioners should be considering for deployment on their own transportation networks. Some of the systems were eliminated because of lack of data. The three systems identified as strong installation candidates were SCATS, ACS-Lite, and InSync. These systems combine lower cost, decreased maintenance, and higher reliability. Table 2.9 shows a brief summary of strength and weakness of these three systems as identified by Selinger and Schmidt (2010) in Adaptive traffic control system in United States, updated Summary and Comparison, Readers should be cautioned that this table is quoted verbatim from the source report and that the original source surveys constitute a small sample size with only four responses per adaptive system. The small sample sizes allow for disproportionate influence by outliers.

Table 2.9: A comparison of cost, reliability, and maintenance among SCATS, ACS-Lite, and InSync

System	Strength	Weakness
ACS-Lite	Fastest installation and fine tuning time of the three	High downtime associated with communication
	Second lowest cost	The least operational benefits
	Ease of use and configurations	Adaptive software cannot change cycle length
		Short high volume periods are missed by the system
InSync	Lowest cost software platform	Video detection was commonly noted as a concern
	Lowest overall weekly maintenance	Communication was noted as a concern
	Lowest percent offline of three systems	
	Highest operational benefits by a large margin	
SCATS	Second Highest operational benefit	Highest cost
	Second Lowest installation and fine tuning hours per intersection	Highest average maintenance per week
	Second Lowest percent offline	

Source: Selinger and Schmidt (*2010*).

Chapter 3: STATICS Modeling

The STATICS evaluation framework can be broken up into three distinct theoretical parts. The first is the underlying traffic model. The second is the control logics built into STATICS for evaluation. The third part is the cost-benefit analysis conducted after performance data have been estimated by the STATICS models.

The underlying traffic model used in STATICS must facilitate the collection of stops and delay information as well as queue lengths. The model also must be capable of simulating the inputs required for traffic signal control logic operation, such as presence detection, gap size and saturation. To maximize accessibility to transportation agency employees, STATICS implementation also required that the model be implemented on a ubiquitous platform, such as Microsoft Excel, which posed a major restriction on complication that resulted in choosing a mesoscopic or macroscopic model over a microscopic one. Likewise, the need for the model to react to relatively small changes in operational logic drove the rejection of macroscopic models in favor of mesoscopic or microscopic models. The confluence of requirements for simplicity and reactivity required the creation and implementation of a mesoscopic model.

The model built into STATICS is a queuing model modified for implementation in Microsoft Excel. This queuing model is designed to separate time steps across cells and allow Microsoft Excel logic and functions to be utilized. Each time step, the model logic advances vehicles, measures queues, determines gap-outs, and records stops as well as estimating travel time and movement saturation. This allows STATICS to implement control logics that react to real-time changes in traffic conditions and measure the operational impact of different arrival patterns on actuated and adaptive systems.

STATICS implements a number of different traffic signal control logics including conventional fixed time and actuated control systems as well as custom adaptive control logics based on the plain language descriptions of the ACS Lite, InSync and SCATS systems. The conventional and adaptive logics read their input data from the current state of the queuing model and decide what signal state to communicate to the model for the next time step. The interaction between these two aspects of STATICS represents a major contribution to the state of the art for traffic signal control evaluation.

The final step in a STATICS analysis is to compare the cost to benefit ratios for tested scenarios. STATICS includes a Cost Benefit Analysis (CBA) methodology designed to allow practitioners and agencies to estimate the total costs of implementing a given set of features or replacement systems. This analysis is designed to allow practitioners and agencies to define costs that they might otherwise overlook. For example, training technicians and engineers to work with a new system is frequently "free" in that the vendor will provide training as part of the purchase. However, this "free" training still consumes engineer and technician time that might otherwise be spent fixing other problems. This cost is frequently overlooked by agencies because labor hours are charged to different budgets than signal control systems. Identifying these and other obscured costs and including them in analyses of traffic signal control systems represents an advancement in the state of the art of traffic signal control system evaluations.

The first step in the creation of the mesoscopic model in STATICS was the simulation of a number of intersection geometries and traffic signal control methodologies to identify which characteristics had the greatest impact on performance. The simulation software chosen was PTV Vision's VISSIM software (PTV Group, 2012) version 5.40. VISSIM is designed so each simulated vehicle makes driving behavior model-based decisions each time step of the simulation. VISSIM allows users to change driver behavior model parameters in order to calibrate model performance to their specifications. VISSIM also enables external programs to control model parameters, such as driver behavior model factors and network features such as signal control status through an external communications framework called the Component Object Model (COM) interface.

Since the advanced traffic signal control features of interest for this research are not available through the built-in functions of VISSIM, customized external modules were needed to implement these control features for simulation experiments. Microsoft C# and .NET framework 4.0 were used to program external control modules to interface with VISSIM for this research. The external control modules, containing the signal control logic, can read and send commands to VISSIM model components via the COM interface. With these external control modules, customized control logics can be simulated as demonstrated by Zhang et al. (2008) and Zhang el al. (2009). The goal of these simulations was to identify the minimum required features to model traffic conditions and the selected traffic signal control logics.

3.1 Experimental Design

3.1.1 Design Factors

To measure the performance of traffic signal control systems and provide selection guidelines for practitioners, a number of factors must be considered. These factors can roughly be broken down into intersection geometric, corridor, traffic, and control factors. A short list of examples can be found in Table 3-1.

Table 3-1: Example Factors

Intersection Geometric	Corridor	Traffic	Control
Approach Lanes	Intersection Spacing	Volume	Phase Order
Left Turn Lanes	Access Points	Turning Movements	Overlaps
Right Turn Lanes	Highway Ramps	Variability	Coordination
Symmetry	Choke Points	Truck Percentage	Pedestrians

There are many more potential factors for evaluation than are listed in Table 3-1. However, if just the listed parameters were tested with three values for each factor, there would be 3^{16} or 43,046,721 combinations. Simulating this number of combinations is not feasible given the resources allocated to the research. Therefore, a more limited set of experimental factors are identified as described in the subsection below.

3.1.2 Core Test Cases

To ensure the reliability of the simulation analysis results and make the best use of limited resources, all factors were carefully screened so that the most important ones are included in the simulation experiments. Efforts were also made to ensure that the selected factors are properly represented in the simulation environment. For example, simulation of access points on corridor segments would require significant additional modeling and calibration work to create two functional intersections with all the routing and turning movement calibrations required to make the various turns into and out of the access point function. Including these elements in the simulation would also make the simulation less general and transferable. With these limitations, a number of simplifying assumptions were made. These are:

- All signals are operated as 8-phase intersections with leading left turns.
- The VISSIM traffic composition default of two percent heavy vehicles is used.
- The intersection approaches are symmetrical geometrically.
- Vehicle traffic dominates intersection performance.

The goal of these simulations is to ensure that the algorithms used to represent each control logic function as intended. Some of the logics like fixed time control are quite simple and easy to implement. Conversely, the algorithm representing InSync, proved to be challenging to implement in a believable manner. Specifically, getting the detection scheme to approximate InSync's video based queue detection and delay estimation algorithms proved to be significantly more difficult than the more conventional detection strategies used by the other systems.

The factors deemed to be of the greatest initial importance are traffic volumes, turning movements, coordination, approach lanes, and right turn lanes. From these factors a variety of test cases were developed. Some assumptions were used to reduce the test cases to a reasonable number. For example, it was assumed that right turn lanes would only be used when right turn movements were high. Similarly, intersection configurations were assumed to be symmetric across the main street and symmetric across the cross street. Table 3-2 shows the factors modeled and the specific values tested.

Several factors were deemed to require more effort to simulate than the results would justify, either from modeling, performance or calibration concerns. Pedestrians would introduce several factors, including pedestrian crossing demand, pedestrian crossing times, and yielding behavior. Most of the corridor factors introduce similar numbers of additional factors. (Note that a simplified pedestrian logic is included in the Excel application.) Access points, for example, introduce the need to generate traffic into and out of the links as well as calibration of routes and turning behaviors. Looking at the use case for the Excel application as a planning tool, it was deemed unlikely that engineers would have sufficient data to accurately account for access point traffic during their preliminary analyses. Similarly, intersection spacing has a direct impact on progression and attendant signal timing issues. Because of these concerns, methods other than simulation were pursued for modeling of these factors.

Table 3-2: Core Test Cases

Test Factor	**Factor Values**	**Number of Values**
Volume Combinations (main:cross street in vphpl)	600:300, 900:300, 1000:300, 600:600, 800:600, 400:200	6
Turning Movements (through/right/left)	80%/10%/10%, 60%/30%/10%, 60%/10%/30%	3
Coordination	Random, Platooned	2
Approaches (main:cross street approach lanes)	3:2, 2:2, 2:1	3
Total Combinations		108

The values in Table 3-2 for the volume combinations are expressed in terms of vehicles per hour per lane (vphpl) on the main street and cross street respectively. Turning movements are expressed in percentages, in the order of through traffic, right, and left. Figure 3-1 shows the various lane configurations used for the different approach and turning movement values. Coordination is either inactive with vehicles arriving as they are randomly generated by VISSIM or coordinated to form platoons using upstream signals. Approaches are reported as the ratio of main street approach lanes to cross street approach lanes. For example, the 600:300 volume combination applied to the 3:2 approach configurations and using the 60%/30%/10% turning movements represents the volume conditions reported in Table 3-3.

Table 3-3: Test Conditions

Movement	Main Volume	Cross Volume
Through	1080	360
Right	540	180
Left	180	60

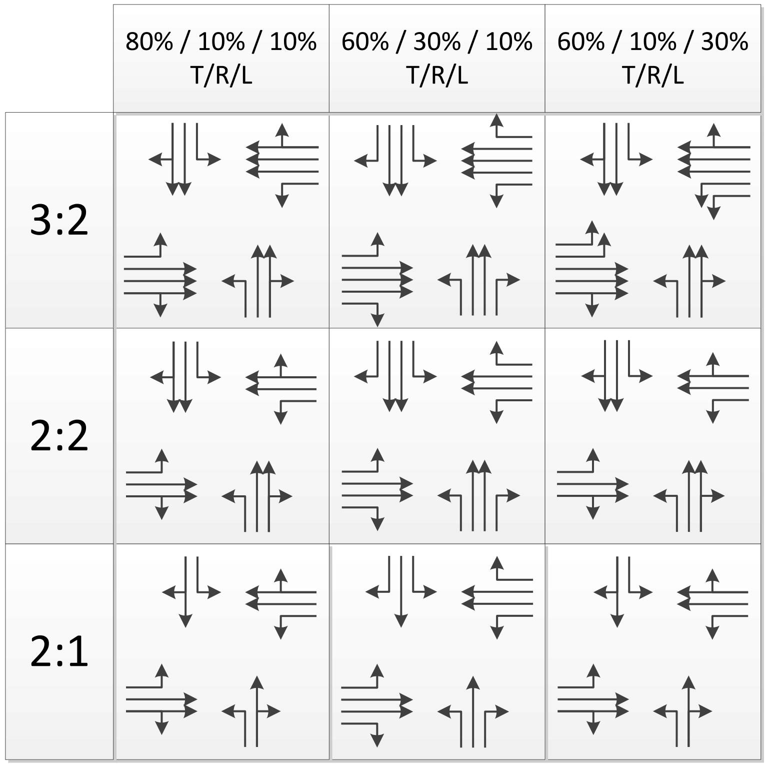


Figure 3-1: Lane Configurations by Approach Configuration and Turning Movement Bias

3.1.3 Simulation Notes

The research team pursued official simulation software for each of the various systems. VISSIM incorporates signal control logic functions capable of simulating fixed time and actuated control. VISSIM Simulation packages exist for SCATS and ACS Lite, but not for InSync. The research team pursued these simulation packages, but the costs to implement them were prohibitive and the restrictions inherent to their use were unacceptable. For example, the SCATS simulation package effectively requires a total system implementation with central server, central system license and vendor configuration for each intersection. To keep all of the system evaluations on common ground, each of the control logics was implemented using C# and the COM, even though fixed time and actuated control could be implemented through VISSIM.

3.2 VISSIM Model Development

3.2.1 Model Creation

In order to simulate the various test cases, a series of VISSIM models were created. These simulation models reflect the intersection geometries shown in Figure 3-1. Key points in model creation include the simulation of right turn on red and the proper operation and calibration of driving behavior where conflicting vehicles interact, such as on free right turns with traffic.

3.2.2 Data Collection

Since the main focus for simulation is the collection of data to supplement field data for use in calibrating the queuing and evaluation models, most of the focus is on simulation data collection. VISSIM simulation enables a number of different detection and data collection systems. These include simulated (loop) detectors, queue counters, travel time measurements, and delay counters. Each element is visible through the COM interface, however, only the detectors are truly helpful in this case since the other measurement systems have their own quirks.

3.2.3 Simulated Detectors

VISSIM's simulated detectors operate like conventional loop detectors with additional features built in that are particularly useful given the computational overhead inherent to communicating over the COM interface. VISSIM detectors provide the standard presence measurement used by real world signal controllers, but they also provide headway between vehicles, measured in seconds since the last car passed over the detector. Detector placement for the simulated intersections is as follows, six foot detectors at 4 feet from the stop bar and advance detectors

165 feet (50 m) upstream of the stop bar detectors. The stop bar detection is slightly unusual with a six foot diameter loop instead of a twenty foot long loop. This is because the consistency of simulated traffic negates many problems with stopping too early and the other features of the simulated detector, such as headway detection, function better with shorter detectors. Note that the intersections were configured for a design speed of 35 mph.

The delay optimization based traffic signal control strategy required a different detection setup. The delay based optimization strategy roughly implements InSync's local optimization strategy, which is discussed in the next section. The key point from a simulation model perspective is that InSync counts vehicles in the queue and checks queue length (Rhythm Engineering, 2012). In order to emulate this input a number of strategies were attempted. The one that proved most successful in simulation is shown in Figure 3-2. It consists of ten 20 foot long detectors in each lane. Because InSync uses video detection to estimate queues there are a number of potential detection issues regarding camera viewing angles, camera height, apparent vehicle size and other video detection error related factors such as occlusion that can't be adequately represented in simulation.

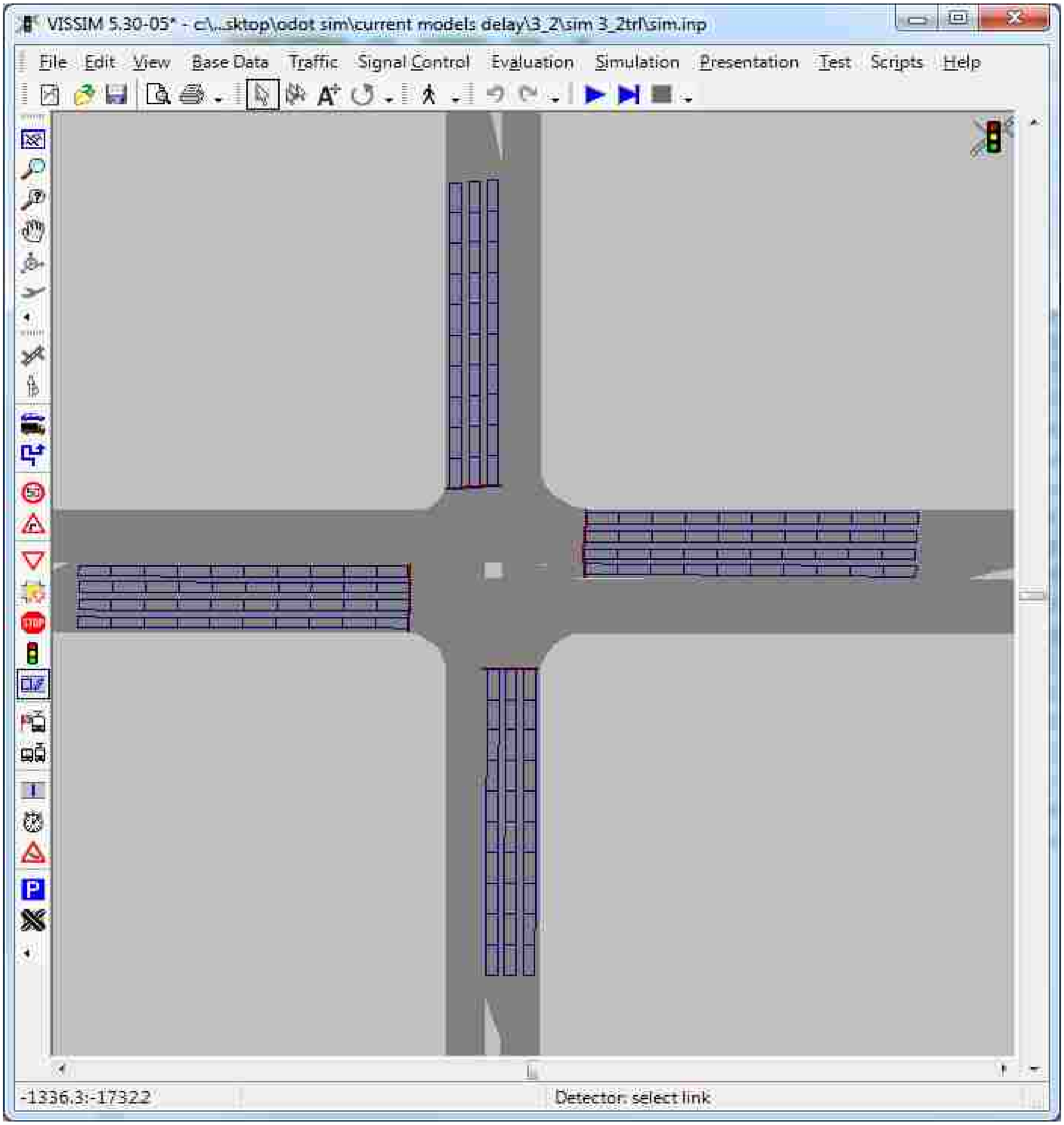


Figure 3-2: Detector Placement for Delay Optimization Strategy

3.2.4 Queue Counters

VISSIM also includes the ability to place queue counters on the network. In this case, queue counters are placed immediately before the stop bar to measure traffic queued at the signal. A queue counter reports the average and maximum queue length during each user specified interval, 30 seconds for this research. Queue counters also report the number of stops within the queue. The number of stops is presented as a total and does not necessarily coincide with the number of vehicles in the queue. This is because vehicles join the queue when their speed drops below a threshold speed, 3.1 mph, and leave it when their speed increases beyond another threshold, 6.2 mph. This means that vehicles can nearly stop, join the queue and leave it again without being recorded as stopping. Changing the thresholds can manipulate this behavior, but not truly eliminate it, so it must be considered in any analysis.

3.2.5 Travel Time

Travel time is measured by a set of data collectors incorporated into VISSIM. Travel times are measured from a start point to an end point on the network. Once a vehicle crosses the starting line, VISSIM begins tracking its travel time until it crosses the end point. Travel times are collected at user specified intervals which is 30 seconds for this research. Travel time is averaged for all vehicles crossing the end point during a 30-second interval. If no vehicles cross the endpoint during an interval, then a travel time of zero is reported.

3.2.6 Delay

Delay is another function of travel time data collection that can be enabled in VISSIM. Delay can be reported two ways, and both are used in this research. The first is at user specified intervals just like travel time and queue counters. In this mode, average delay is reported for each interval with additional information that includes the average time stopped and average number of stops. The second method of reporting is the raw data. In the raw data, each vehicle that enters the travel time segment and the delay it experiences during its trip is recorded.

3.2.7 Calibration

Calibration is a very important step for any simulation research. At the intersection level, calibration efforts are dedicated to deciding parameter values of the driver behavior models. There have been numerous papers detailing strategies for selecting the optimal calibration parameters. One paper by Park and Qi (2005) has recommended a calibration procedure and parameter values used by other studies. Given the similarity of their case study work to this project, the research team chose to use their parameter values directly for this study.

The VISSIM simulation software is capable of utilizing two different driver behavior models when simulating traffic. The manual suggests utilizing the Wiedemann 1974 model (Wiedemann, 1974) for urban simulation and the research team followed this suggestion. The Wiedemann 1974 model and other VISSIM behavior model factors provided by Park and Qi (2005) and used to calibrate these simulation models may be found in Table 3-4.

Table 3-4: Default and Calibrated VISSIM Driver Behavior Parameter

Parameter	Default	Calibrated	Model
Average Standstill Distance	6.6	12.6 feet	Wiedemann 1974
Additive Part of Safety Distance	3	5	Wiedemann 1974
Multiplicative Part of Safety Distance	3	5.3	Wiedemann 1974
Look Ahead Observed Vehicles	2	4	General Following
Maximum Look Ahead Distance	820	706 feet	General Following
Minimum Gap Time	3	4 sec	Priority Rules
Minimum Headway	16.4	65.6 feet	Priority Rules

One parameter that was not addressed by Park and Qi (2005) was the waiting time before diffusion. VISSIM occasionally has vehicles get into situations where a desired lane change or other behavior, such as yielding can cause a vehicle to stop in place for indefinite periods of time. This most commonly occurs with permissive turns where a vehicle stops and then can't accelerate fast enough to make it through gaps in oncoming traffic. Since stopped vehicles generate queues and block other vehicles, VISSIM tracks them for a time and if they remain deadlocked for longer than the waiting time before diffusion parameter VISSIM removes the vehicle from the network.

Unfortunately, the queues that such vehicles leave behind are not magically corrected. This can lead to rather significant disruptions. The default value for waiting time before diffusion is 200 seconds. This was found to be too long. This time was lowered to one minute, which was found to be the best compromise between diffusing legitimate vehicles and not diffusing deadlocked vehicles quickly enough.

3.3 Data Collected

Table 3-2 details the distinct test cases created for each signal control system (time of day, traffic responsive, actuated, fast occupancy, slow occupancy and delay optimization) being evaluated. With each system being subjected to 108 test cases, large amounts of data have been collected. Each intersection generates twelve travel time and delay measurements and eight queue counters per test at a rate of one record each 30 simulation seconds and a raw delay entry per vehicle that enters the network. Even reducing these numbers to averages presents a staggering amount of data.

The data itself is stored by VISSIM in text files. The research team has written programs to read the raw files and upload the data to a database for analysis purposes. Millions of rows of data have been collected. Because of this volume of data, it is impractical to display even a small fraction of it here. Instead, a selection of charts showing some interesting results is presented here.

The first chart shows the impact of platoons on signal performance. Figure 3-3 shows the average vehicle-seconds of delay data for each movement at an actuated control intersection under random arrivals and strong platoons. Delay is measured in vehicle-seconds, the total number of seconds each vehicle waits, added together, so that small delays on high demand movements are accounted for with the same relative weight as long delays on low demand movements. The intersection in question is configured as a 2 lane approach main street with left turn lane and a 1 lane approach plus left turn lane cross street. The data was collected under the 600 vphpl main street and 300 vphpl cross street volume condition.

The impact of platoons on vehicle delay is quite clear in Figure 3-3. Delay decreases by over 80 vehicle-seconds for the east and west bound through movements. Likewise, delay is reduced for the cross street when it receives progression and platooning. Cross street delay was reduced by 15 vehicle-seconds on average.

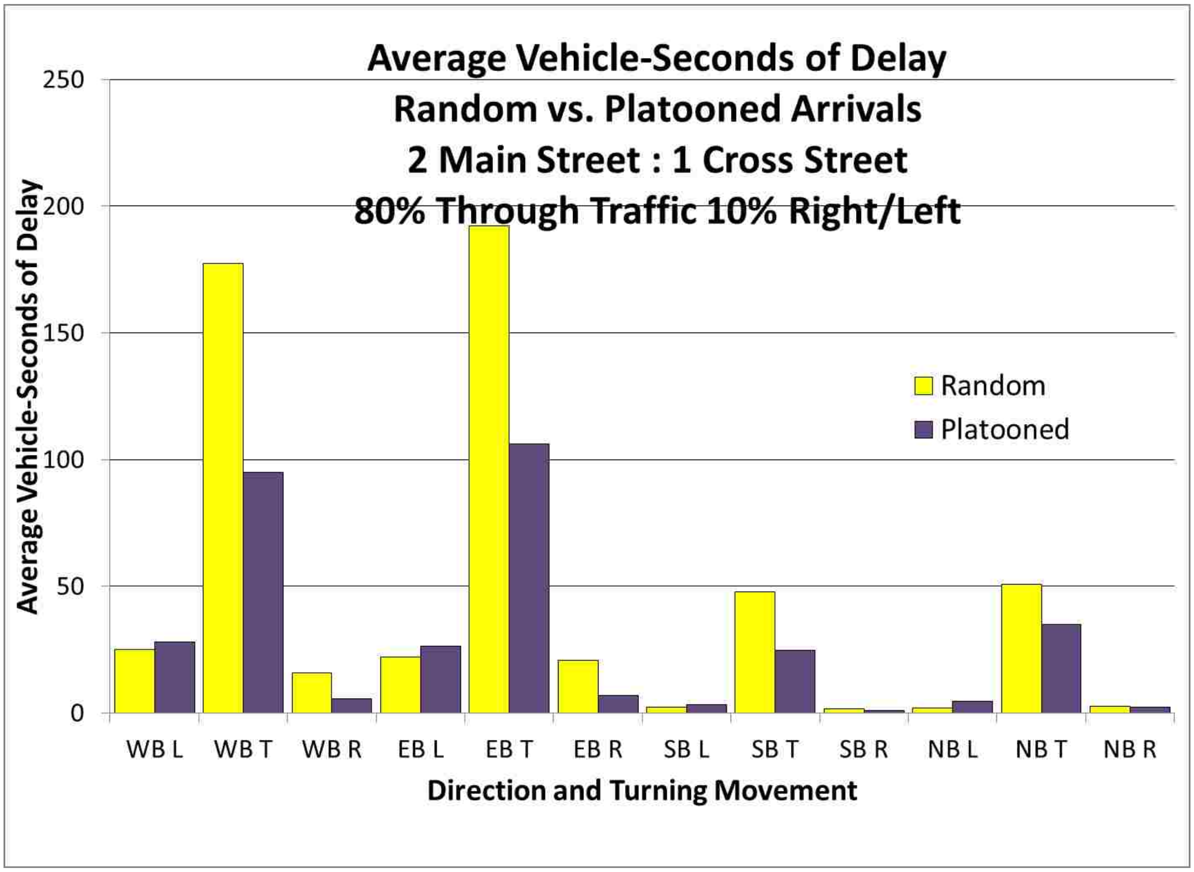


Figure 3-3: Average Vehicle-Seconds of Delay by Movement at 2:1 Intersection Under Actuated Control with 600:300 vphpl Input Volumes

Figure 3-4 gives an idea of the performance difference between actuated control and the SCATS-like fast occupancy based control algorithm. The test intersection and volume levels are the same as the previous intersection. For this comparison both systems are operating with platooned arrivals. The fast occupancy control strategy created by the researchers is able to adjust its cycle length and splits within relatively wide margins, which gives the system greater flexibility than the actuated system to respond to traffic arrivals. An examination of the two algorithms showed that fast occupancy gained its performance benefits from being able to adjust its maximum times to serve peaks in demand. This resulted in fewer cycle failures and the commensurate reductions in delay.

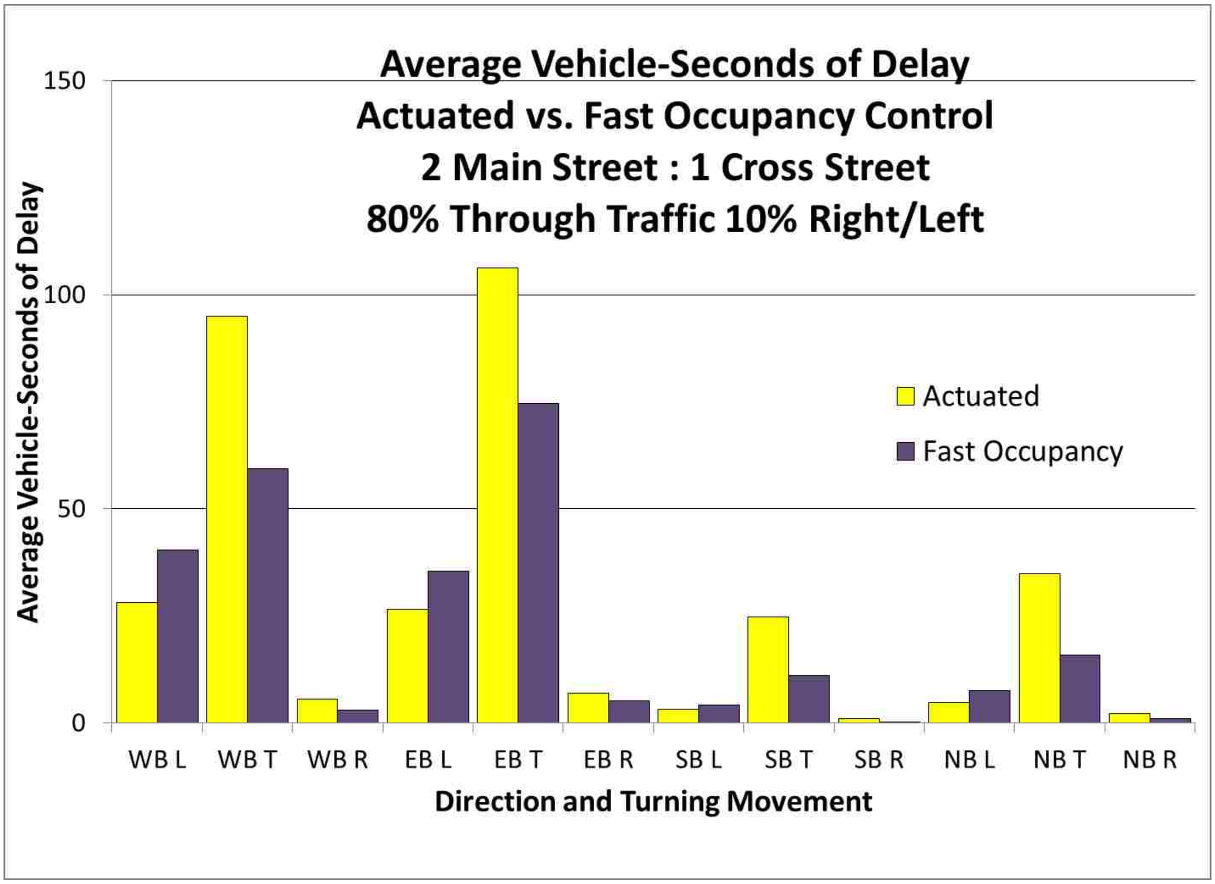


Figure 3-4: Vehicle-Seconds of Delay for Actuated Control vs. Fast Occupancy Algorithm Under Platooned Arrivals

The simulation data collected is useful for two reasons. The first is that the research team can setup simulations to test model accuracy by providing exact conditions to test the models on. The second is that simulation data can be used to calibrate models when behavior is uncertain. It is for this reason that many of the test cases are near saturation. Intersections that are approaching saturation have the greatest unpredictability and the greatest need for accurate modeling.

3.4 Model Logic Construction

The design and implementation of the STATICS package in Microsoft Excel enforced a number of constraints. The performance of macros and programming run using the built in Visual Basic for Applications (VBA) depends heavily on the extent to which built in Excel functions are used (or extensive effort is made to program custom functions to a similar level), knowledge and control of the calculation process, and CPU single-threaded performance. These limitations and design concerns limited the complexity of model that could be put into the STATICS package.

The model eventually selected to underlie STATICS was a queuing model. Queuing models have been used in transportation to predict intersection performance and predict measures of effectiveness such as average and total delay (Ruskevich, 2011; Mannering, et al., 2007). There are numerous queuing models that may be applied to an intersection and several different terminologies surrounding them. For clarity, the terminology that will be used here will follow Kendall's notation (Kendall, 1953). Kendall's notation denotes a queuing system in the form of Arrival Type/Service Type/Number of Servers. In this notation the arrival and service distributions are described by the letter D when the distributions are deterministic and the letter M when the distributions are stochastic. A few example stochastic distributions are the Poisson and Gamma distributions. Following Kendall's notation a queue with deterministic arrivals and deterministic departures with one server would be a D/D/1 queue. If arrivals were to be regarded as following a Poisson distribution, but departures were still deterministic, the queue would be denoted M/D/1 instead. A third letter, G, is used to denote the use of a general distribution, i.e. no special assumptions about the distribution of arrivals or departures.

Looking at traffic patterns inherent to corridor operations there are some different ways to apply queuing theory based on the assumptions made regarding vehicle arrival and departure patterns. For this project, the research team is assuming that saturated flow has a uniform distribution with upper and lower bounds. Similarly, arrivals from outside the network are assumed to be Poisson distributed with exponentially distributed headways except when the traffic flow is saturated. Note that while arrivals from outside the network are considered to be Poisson distributed, the arrival rates used to generate the specific distributions used will be varied based on expected arrivals from upstream.

A sampling of queues and queuing cases can be found in Table 3-5, below. In the model each queue has servers up to the number of lanes dedicated to that movement (denoted by # Table -3-1). An interesting queue to look at is the free right turn on red queue. It uses Poisson arrivals and looks at the headways of conflicting vehicles to determine when to serve a vehicle, if it wishes to turn right, otherwise it reverts to a deterministic departure rate of zero until the light turns green. Side street left and right turning vehicles likewise have service distributions based on thresholded exponential distributions to simulate gap acceptance behavior (Ragland, et al., 2006). Note that a Poisson arrival distribution has a Gamma distribution of headways.

Table 3-5: Example Queues

Case	Queue	Arrivals	Departures
Red Light (Through Traffic)	M/D/#	Gamma	0
Red Light (Free Right Turn)	M/M/1	Gamma	Headway>Min. Gap, 0
Green Light With Queue	M/M/#	Gamma	Departure headway
Arrival on Green	M/D/#	Gamma	Infinite or Arrival Rate
Side Street Permitted Left Turn	M/M/#	Gamma	LT Arrival headway > Sat. Headway and Through Headway > Min. Gap

The distribution of headways and arrivals is important to consider when side street and permitted left turn traffic is included in the analysis. An average or uniform headway assumption would lead to the conclusion that there are no windows for vehicles to make turns onto the main street after traffic reaches a threshold volume where the average gap is smaller than the acceptable gap. In reality, vehicles are not so evenly distributed and there will be usable gaps even with traffic flows high enough for the average gap to be unacceptably small.

3.5 Monte Carlo Method

The Monte Carlo Method (MCM) was published by Metropolis and Ulam (1949) as a means of solving complex problems with difficult probabilistic and combinatorial aspects. One example used in their description of the method is a game of solitaire. Computing the probability of winning a game of solitaire is a surprisingly difficult endeavor because the order of cards in the deck and the individual stacks, as well as the order of plays all impact the probability of winning. The solution proposed by Metropolis and Ulam (1949) was to simply "play" a sufficiently large number of games that the law of large numbers would dictate that their computed solution would be close to the actual probability of winning a game of solitaire.

Applying this concept to the problem of predicting traffic signal system performance and the queuing theory discussed previously, allows the creation of a methodological framework applicable to Excel that can be used to not only compute average benefits, but also examine the variability of those benefits as well. Through the use of randomization and explicit or assumed variabilities, the proposed framework can be used to measure the performance of varying traffic flows and arrivals on the performance of the signal system. Another important benefit is that adding variability to the system may expose particularly good or bad operational conditions. As an example, consider how performance could be expected to vary when operational conditions are near to saturation. If average performance and deterministic traffic flows are used, the estimated performance could be quite different from observed performance where traffic flows may be oversaturated at times.

3.6 Performance Estimation

Vehicle delay can be estimated, both on an individual and on average basis, from the queuing diagram method shown in Figure 3-5. For an isolated intersection, assume that the vehicle arrival rate is uniform, as shown in Figure 3-5, then the area of the shaded triangle is the total delay in one cycle for that phase and the average delay for each vehicle can be defined as Equation 3-1, below

$$\bar{d} = 0.5r \cdot (\overline{q_a} t)/(\overline{q_a} C) = 0.5r \cdot t/C \qquad (3\text{-}1)$$

Where r is the effective red time; *t* is the time needed to clear the queue in one cycle; $\overline{q_a}$ is the average arrival rate; and *C* is the cycle length.

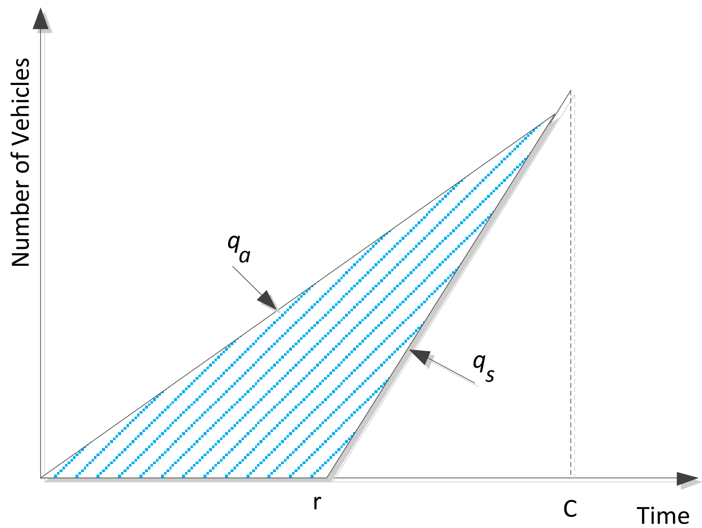


Figure 3-5: Arrival and Departure Curves with Uniform Arrival Rate

Assuming that the intersection does not congest, the total vehicle arrivals should equal the total vehicle departures. This gives us Equation 3-2.

$$\overline{q_a}t = (t - r)q_s \tag{3-2}$$

Where q_s is the saturation flow rate. The departure flow rate, q_d, is assumed to be the saturation flow rate while a queue exists. After the queue has discharged, the departure rate will reduce to the arrival rate, q_a. Rearranging (3-2), the estimation of t can be

$$t = rq_s/(q_s - \overline{q_a}) \tag{3-3}$$

The total number of stops can be calculated from the number of vehicles stopped in the queue

$$N_s = tq_d = rq_sq_d/(q_s - \overline{q_a}) \tag{3-4}$$

The average number of stops

$$\overline{N_s} = tq_d/Cq_d = rq_s/C(q_s - \overline{q_a}) \tag{3-5}$$

The maximum queue length

$$Q_{max} = rq_d \tag{3-6}$$

The saturation for phase *i*

$$Sa_i = Cq_d/q_s(C - r) \tag{3-7}$$

For coordinated intersections, the percentage of vehicles which arrive on green and can go through the intersection without any delay will be determined by how strong the coordination is. Assuming that the percentage of vehicles passing through the intersection without stopping is P_{d0}. The average number of stops is then trivial to calculate

$$\overline{N_s}^c = 1 - P_{d0} \tag{3-8}$$

As shown in Figure 3-6, the shaded area is the total delay in one cycle, the average delay for each vehicle under coordinated conditions can be defined as

$$\bar{d}^c = 0.5r(1 - P_{d0}) \tag{3-9}$$

The maximum queue length

$$Q_{max} = rq_{ar} \tag{3-10}$$

Where q_{ar} is the arrival rate during the red time. When the corridor is well coordinated, q_{ar} is much smaller than the average uniform arrival rate $\overline{q_a}$. Note that the saturated flow rate is the same as in the isolated intersection case.

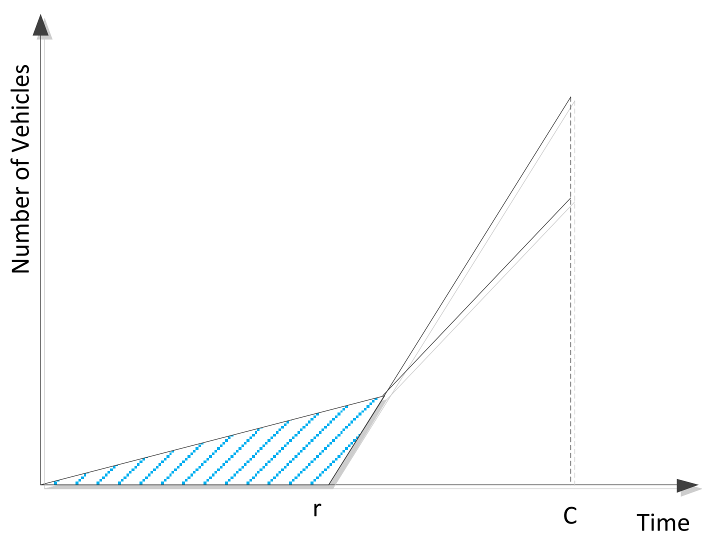


Figure 3-6: Arrival and Departure Queuing Diagram for a Coordinated Intersection

When these methods are applied to an Excel spreadsheet with MCM varied arrivals and departures calculated based on small discrete time steps, there are subtle changes to the equations. Queuing for example can be implemented in the form of Equation 3-11.

$$Q_{i,j} = Q_{i-1,j} + \sum q_{a\,i,j} - \sum q_{d\,i,j} \quad (3\text{-}11)$$

Where $Q_{i,j}$ is the phase j queue in interval i. This value is determined based on the i-1 interval's queue for phase j, $Q_{i-1,j}$, plus the sum of arrivals for phase j during interval i, $\sum q_{a\,i,j}$, and minus the departures for phase j during interval i, $\sum q_{d\,i,j}$. Using the arrival distributions and MCM described previously in the Excel spreadsheet will impact the queue by changing the arrival and departure rates. Specifically, arrivals and departures will not form straight lines. They will be stepped as arrival and departure information is processed each time step in the model. By looking at the average and maximum values it is possible to gather the relevant performance data and identify intervals with problems such as queues blocking upstream intersections.

Another important aspect of the implementation in Excel is that significant amounts of data need to be collected just to emulate the various control strategies. For example, the number of vehicles in the queue is important to running InSync's optimization algorithm because it seeks to minimize total vehicle-seconds of delay per phase (Rhythm Engineering, 2012), which requires knowledge of how many vehicles are waiting in the queue during any given interval to calculate. There are corollaries for the other systems as well, such as needing the phase saturation levels for ACS Lite's algorithm (Gettman, et al., 2006). Because many of the performance measures need to be calculated for operational reasons it is fortunate that it is relatively trivial to gather fairly complex performance data from the model.

The description of the model has been in terms of uniform distributions to this point to make it easier to understand the transition to the queuing model implementation in Microsoft Excel. The Microsoft Excel implementation sums values in cells and does not need to explicitly consider arrival distribution because that function is taken care of independently in another cell executing a function, as opposed to a hardcoded part of the model operation. For example, the queue length is a function of the number of vehicles waiting in the queue and the number of lanes available to store those vehicles. If 12 vehicles are in a movement's queue and that movement has two lanes associated with it, there would be an expected queue length of 6 vehicles. Similarly, there would be a 4 vehicle queue for three lanes. Total vehicle delay measurement becomes a time integral calculated as the sum of the number of vehicles in the queue during each interval multiplied by the interval length. Average delay is total delay divided by the number of vehicles passing through the queue. The number of vehicles passing through the queue is also the throughput or volume measured for that phase.

Figure 3-7, below, shows an example queuing diagram using one second intervals and random arrivals (solid blue line) and departures (dashed red line). The queue length, assuming a single lane for queuing, is shown with the dotted green line. The total delay incurred by the queued vehicles is represented by the purple dash-dot line. In this case 12 vehicles arrive over 30 seconds and depart over 15 seconds. During that time, a maximum of 4 vehicles reside in the queue at any given moment and a total of 36 veh.-sec. of delay are incurred. This works out to an average delay of 3 seconds per vehicle. Saturation can be calculated by dividing the number of vehicles discharged during the green interval by a user supplied saturated flow rate. For this example, the queue is served by two lanes. 1,800 vehicles per hour per lane will be used as the saturated flow rate. Using these numbers, the queue discharged at a rate of 0.8 veh./sec. which is 80% of the saturated flow rate of 3,600 vehicles per hour (2 lanes at 1,800 veh./hr./ln.), which works out to 1 veh./sec. Vehicles arriving after the queue has cleared are immediately discharged and do not add to the queued vehicles or vehicle delay. Note that the synthetic saturation would be expected to be different from a loop detector's occupancy reading as vehicle lengths and speeds are not being used to calculate saturation.

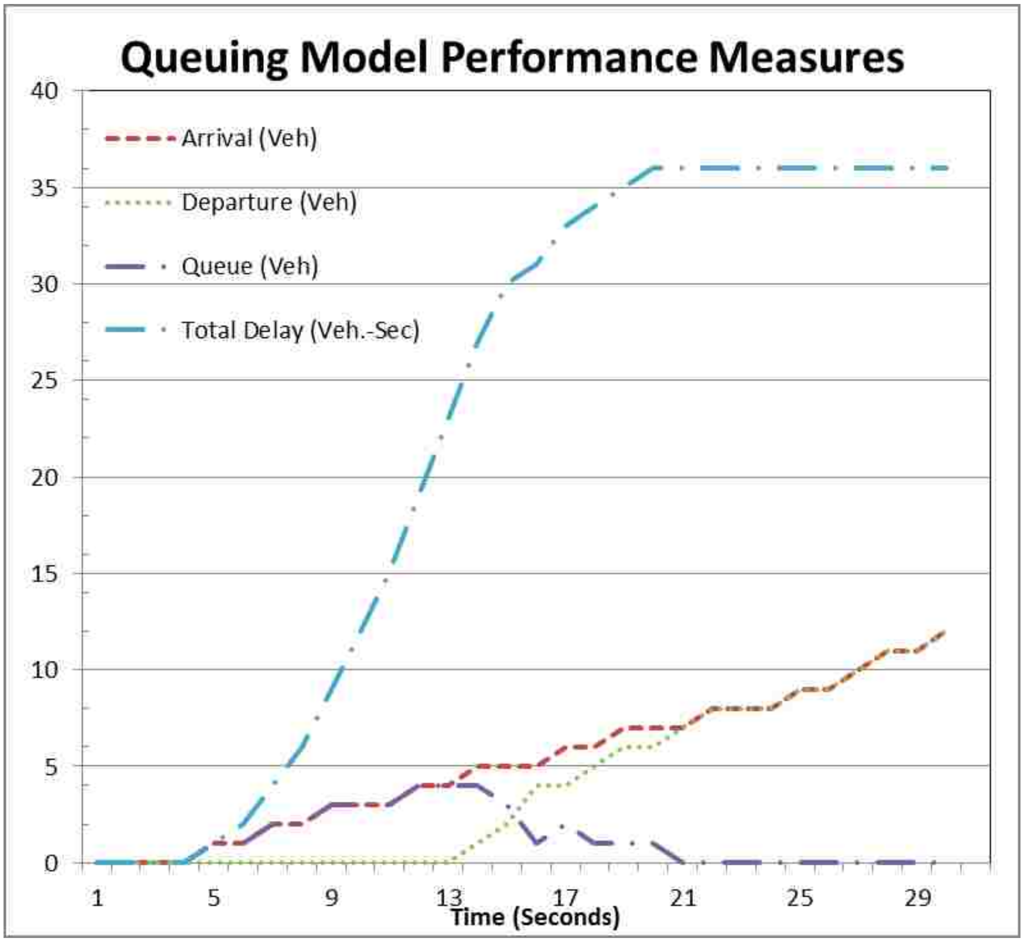


Figure 3-7: Arrival and Departure Diagram for Discreet Time Intervals with Queue Length and Total Delay

3.7 Network Construction

When estimating the performance of a traffic signal system, it is important to accurately represent the network that the system will be deployed upon. To this end, the queuing model and MCM will be used on a network consisting of major intersections, minor intersections and segments. Major intersections are signalized and accept data inputs for all movements at the intersection as well as pedestrian crossing counts. The approaches to major intersections may also have lane layouts that are different from their connecting segments. Segments span from stop bar at an upstream intersection to the stop bar at the downstream intersection and may have a different number of lanes in the upstream and downstream directions. Minor intersections are located along segments between intersections. Minor intersections serve to allow the system to correct for volume differences between volumes headed downstream from a major intersection and those observed at the downstream intersection. If volumes increase downstream than the volume added at a minor intersection will be positive and vice versa. This volume leveling function also serves to break up platoons because vehicles are randomly added or subtracted as needed.

Network construction is an essential function of the queuing and evaluation logic that is built into the Excel application. Each queue needs to be linked to an arrival source and departure sink. By default, each intersection has twelve queues, one each for through, right and left movements on four approaches. Different choices regarding intersection geometry enable or disable different queues. For example, a right turn queue would be linked to a through movement queue if there is not a right turn only lane and right turns are allowed. If right turns are prohibited, the right turn queue would be completely disabled. Similarly, a T-intersection would disable the unused approach queues. Additional construction logic is required to link queues to departure lanes, an eastbound left turn, a westbound right turn and a northbound through movement all discharge to the northbound segment associated with that intersection. These linkages are used to determine if permitted movements may discharge and what volumes are seen at downstream intersections.

3.8 Traffic Signal Control

To apply this queuing model methodology to signal control system evaluation, each queue must be assigned to a signal control during network construction. The signal control logic seen by each queue is very simple. The control logic either gives the queue a "red light" during which no vehicles may discharge, a "green light" which indicates that traffic should discharge at the saturation flow rate, or a "permitted" indication which requires the queue to wait for a sufficient gap in conflicting movements before discharging a vehicle.

Note that the walk signal is not tracked in a directional manner. Specifically, the system does not track whether the pedestrian is crossing east to west or west to east. This is important because permitted movements receive a "red light" when they would intersect a crosswalk during the walk signal. This means that permitted lefts and rights will not discharge while the relevant crosswalks are receiving the walk signal. Also note that as implemented, all crosswalks are outside of the right turn lane, so right turns will always be affected by crosswalks.

Similarly, the traffic signal control logics need to have input from the queuing model in order to drive their logic. For example, under actuated control the existence of a queue can be interpreted as a presence call. Saturation and delay are other model outputs that can be used by control logics. The control logics responsible for controlling which queues get which indications at which times and how they allocate those indications will be discussed in Chapter 4

Chapter 4: STATICS Signal Control Implementations

The queuing model discussed in Chapter 3 forms the theoretical heart of the analytical engine implemented in the STATICS application. However, it does not represent the sum total of the logic needed to operate the analytical engine. There are numerous other factors, such as intersection configuration and specific control logic details that must also be input and enforced.

One of the challenges to implementing STATICS is to recreate the various signal control logics and ensure they work. Some of the signal control logics are complicated enough that, even if the proprietary algorithms were available, it would be impractical to implement all of their features in a Microsoft Excel application. This is particularly true for the adaptive algorithms. The goal of implementing the various strategies in simulation was to find the minimum required feature set necessary to replicate the control logics.

There are three aspects of the analytical model that will be discussed in this chapter. The first aspect is the required input data. The second is the signal control logic. The final aspect is the output data generated by the model. Each aspect builds upon the queuing model. The input data controls which queues are active and what vehicle flows are present. The signal control logic controls queue service. Finally, the output data is gathered from the queuing model.

4.1 Required Model Input Data

Performing the desired in-depth analysis of individual intersections or a corridor that is needed to recommend the implementation of a particular traffic control system requires a significant amount of data collection work. The necessary datasets fall into many categories but can be roughly broken down into geometric, volume, and control categories. In designing the analytical framework, efforts have been made to minimize data collection cost and analytical complexity.

4.1.1 Geometric Data

Geometric data outlines the fixed features for the corridor. This includes the number of lanes on intersection approaches, speed limits, and saturation flow rates. These factors determine the capacity, or how many vehicles can pass through the intersections per hour. Further information includes approach configuration and the length of road segments linking intersections, both of which impact progression on a corridor. As was briefly discussed regarding model network construction in Section 3.7, there is a respectably large amount of data needed regarding details such as exclusive right turn lanes, approach lengths, existence of pedestrian crosswalks, etc.

4.1.2 Volume Data

Volume data is a required input for evaluating the performance of a signal control system. Due to the variation in how the various systems record data and what data they record, it became obvious that a single, basic format was needed. It would have proven burdensome to require data not collected by more basic systems, as well as counterproductive in light of the project's goal of determining whether to replace such a basic system with a more advanced implementation. Additionally, the project was intended to develop a planning level tool, not a microsimulation model which would require such detailed data.

To make the evaluation methodology as accessible as possible, the research team and ODOT technical advisory committee decided that 15 minute interval through, right and left volumes as well as pedestrian actuations per 15 minute interval would be used. This standard of volume data collection can be met very easily by basic data collection methods, such as tube counters. With ODOT currently using the Wapiti W4IKS and Northwest Signal's Voyage software at the majority of their intersections, it should be easy for practitioners to gather sufficient input volume data.

There are two concerns to address when using automatically collected data from the existing signal control systems. The first concern regards a set of W4IKS data provided to the research team that came from the 99W corridor prior to the installation of 2070 controllers and the Voyage software. It consists of volume data from twelve channels, each of which may include more than one loop detector, aggregated in fifteen-minute intervals. These tied together loops pose a problem. When multiple loops occupy the same detector channel, the channel will only add one volume count to the bin when any of the tied together loops are occupied. This is not a problem for one loop, but may result in two vehicles counting as a single vehicle when two loops are tied together. The more loops that are tied together, the greater the potential impact on the reported volume as more simultaneously arriving vehicles are miscounted. Wu, et al. (2010) developed a probabilistic method for correcting the volume counts based on the probability of one or more vehicles arriving at the same time given the current volume level.

The other concern of note when using detector data is that combined movement lanes or channels have a single volume record. This means that it may be impossible to accurately discern the number of right turning vs. through movements for a combined through and right turn lane from detector data alone. This problem becomes more acute for combined through, right and left turn lanes. While such lanes may not be common on the mainline of the corridor, they would be expected to occur on side streets. In these cases it may be necessary to use tube count data or to split detector data based on previous tube count results.

4.1.3 Timing Plan Features

There are a number of frequently implemented traffic signal control techniques that the evaluation logic implements in addition to the control logics. These include right turn overlaps and two varieties of left turn phase reservice. These features have specific requirements for implementation in the field and in the evaluation logic.

Right Turn Overlaps

Right turn overlaps allow right turns to get green lights out of the normal sequence and separate from their corresponding through phase. Using Figure 4-1 as an example, the phase 2 right turn can be overlapped with the phase 3 left turn. This is allowed because the two movements do not conflict. However, there are implementation requirements. The overlapped right turn requires a separate right turn lane and a separate signal head to give independent right turn control. Because of these requirements, the selection of right turn overlaps is made during intersection geometry data input, rather than during timing plan creation. It is assumed that a right turn overlap is always used when the intersection is configured to be able to do so. Overlaps may be implemented with any signal control logic.

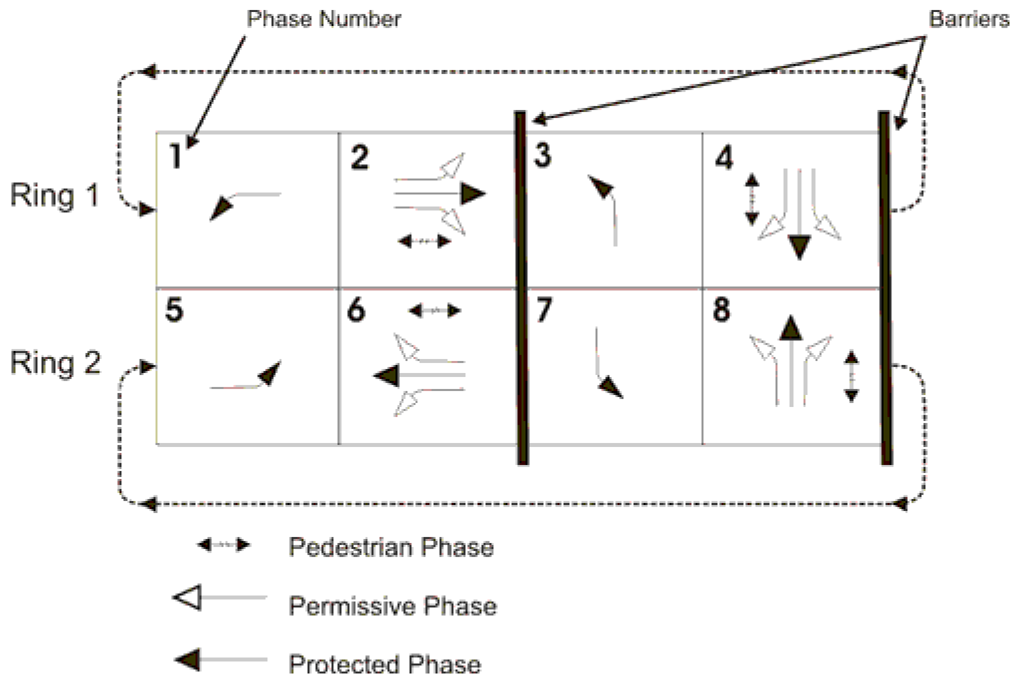


Figure 4-1: NEMA Phasing Diagram (FHWA, 2012)

Left Turn Phase Reservice

Left turn reservice comes in two varieties, fixed and conditional. Fixed reservice will always reserve the left turn phase while conditional reservice looks at a combination of opposing and concurrent through traffic conditions to determine whether to bring up the left turn phase again. It should be noted at this point that conditional phase reservice is a NEMA specification (NEMA, 1998) that may be incorporated into numerous systems. Voyage software includes a feature called coordinated late left turn that operates slightly differently (Northwest Signal Supply, 2009). Specifically, the NEMA standard requires the barrier to be crossed after left turn reservice while coordinated late left turn is allowed to return to the coordinated phases if there is no demand for other phase service. Under most traffic conditions there should be little difference between the two algorithms because traffic demands should be high enough to put some demand on opposing phases, which causes coordinated late left turn to behave the same as the NEMA specification.

Left turn phase reservice is available to all conventional control logics, and the fast occupancy and slow occupancy adaptive logics. The delay optimization control logic has no need of phase reservice techniques because it does not follow a fixed phase order or adhere to a cycle length. Conditional left turn phase reservice is only available to the advanced actuated control logic.

Left turn phase reservice, conditional or fixed, requires that the left turn in question be a leading left turn. This is so that the left turn can be served a second time before crossing the barrier. A conventional phasing diagram for comparison with the left turn phase reservice diagram is provided as Figure 4-1. An example NEMA phasing diagram for left turn phase reservice may be found as Figure 4-2. When reservice occurs, it changes which phases can cross the barrier. In Figure 4-1 phases 2 and 6 were required to terminate before the barrier could be crossed and phases 3, 4, 7, and 8 served. For left turn reservice of phase 5, as shown in Figure 4-2, phases 2 and 5 can cross the barrier. For conditional reservice of phase 5, phases 2 and 5 could cross the barrier if the left turn is reserved, otherwise phases 2 and 6 would be required to cross the barrier.

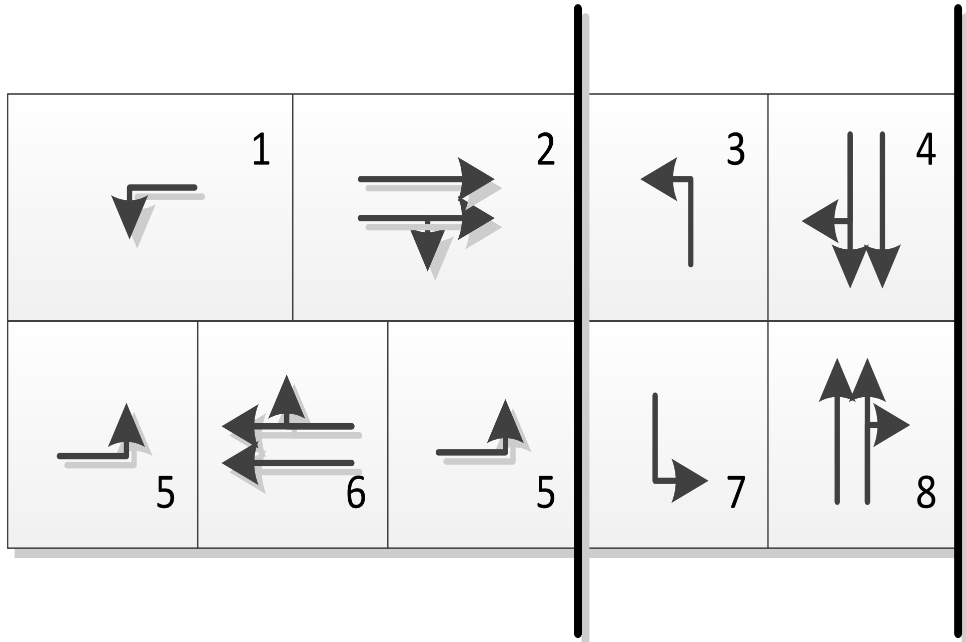


Figure 4-2: Left turn phase reservice

4.2 Operating Constraints

There are numerous operating constraints that the signal control logics must adapt to. These include phasing issues and preferences and pedestrian impacts among others. In general these constraints enforce restrictions on phase orders, service times and whether certain movements are valid.

4.2.1 Pedestrian Phase Impacts

Pedestrian service is a commonly encountered constraint on signal control. When considering a corridor, it is common for the corridor phases to enjoy longer relative service times and for the corridor to be the larger of the two streets at an intersection. This tends to make pedestrian crossings of the cross street simple, because the shorter crossing distance is associated with the longer allowed time to cross. Pedestrians crossing the corridor, however, present a problem. In general, streets crossing the corridor require less time to serve their vehicle demands and more time is required for pedestrians to cross the larger street. In this case more service time needs to be allocated to the cross street phases in order to properly serve the pedestrian movement(s).

4.2.2 Phasing

There are a number of geometric design details that influence phasing. These influences may restrict which phase orders can occur, or they can prevent certain phases from existing. There are two major constraints specific to intersection geometry that were taken into account in the application, restricted phasing and T intersections.

Restricted phasing is used when two movements that would normally be compatible with each other are for some reason incompatible. Typically this occurs with left turns where the intersection geometry would cause opposing left turn arcs to occupy the same space. Since these two left turns can no longer be phased together, a number of restrictions come into play. First, the relevant left turns are restricted to lead-lag phasing since the two left turns cannot be served simultaneously as they would in lead-lead or lag-lag phasing. Second, the concurrent through phase is required to be served for a minimum time between the leading and lagging left. The new NEMA phasing pairs for phases 1, 2, 5, and 6 under restricted phasing are 1 and 6, 2 and 6, and 2 and 5. Note that 1 and 5 is no longer valid.

Another common phasing restriction is the T-intersection. Currently, T intersections are only supported for side streets; there is no option to implement a T-intersection where the corridor ends in a T-intersection. With T-intersections one of the side street approach legs is removed. This means that there is no volume input from those phases, any movement that would turn into the affected leg is deactivated and so on.

Using Figure 4-1, consider removing the phase 3/8 leg of the intersection as an example. Phases 3 and 8 cease to exist because that leg has been removed. The phase 1 left turn has nowhere to go and is eliminated. Phase 4 is reduced to right turns only and phase 2 right turns are not allowed. This restricts the available phases and which phases are allowed to start a cycle. In this case phases 1, 3 and 8 have been eliminated which reduces the 16 possible starting phases to 2 (2457 and 2467). This reduces the valid phase pairs dramatically as well, now only 2 and 5 and 2 and 6 are valid for the first side of the barrier and only 4 and 7 are valid for the second.

4.3 Implemented Control Logic

This is the core piece of the research which everything else either builds upon or supports. In total there are three conventional and three adaptive control logics implemented in the STATICS computational engine. This will give practitioners significant control over the evaluation process. The flexibility afforded by the multiple signal control systems should make it easier to evaluate diverse signal control systems and some advanced features can be enabled on advanced implementations.

Because of the proprietary nature of several of the algorithms and the limitations of Excel, it was not possible or practical to implement complete control algorithms for each system and system feature. It would have also been prohibitive in terms of data entry and possibly contrary to the goal of having a planning level model to have delved into such fine details. Because these systems are either simplified versions or translations of the plain English descriptions of the systems, it is important to descriptively name the control strategies distinctly from their ideological parents to prevent confusion about what signal control logic is being used.

4.3.1 Control Phasing

Figure 4-1 shows a typical NEMA phasing diagram. To eliminate confusion as much as possible, NEMA phasing was adopted notation for all systems. For convention, phases 2 and 6 are the corridor phases and phases 4 and 8 are used for the cross street. For consistency phase 2 travels in the ascending intersection number direction. For an east-west corridor with intersections numbered from east to west, the phasing would be as shown in Figure 4-1. For a north-south corridor numbered from north end to south end, phase 2 would be the southbound direction and phase 6 the northbound direction.

An important fact to consider that may not be evident to readers unfamiliar with NEMA phasing is that certain phases may be active at the same time while others are prevented from acting together. For example, phase 1 (the westbound left turn in Figure 6.1), may be active at the same time as phase 5 (the eastbound left turn) or phase 6 (the westbound through). Phase 1 may not be active at the same time as phase 2 (the eastbound through) or any of the phases on the other side of a barrier; phases 3, 4, 7 and 8.

For leading left turns, as shown in Figure 4-1, the valid corridor active phase pairs are 1 and 5, 1 and 6, 2 and 5 and 2 and 6. These pairs are reached in the following manners. Phase pair 1 and 5 as leading left turns, start the process. Phase pair 1 and 6 would become active when phase 5 terminates before phase 1. Likewise, phase pair 2 and 5 becomes active when phase 1 terminates before phase 5. Phase pair 2 and 6 would become active in one of three ways; the first is if both phases 1 and 5 terminate simultaneously, the second is coming from phase pair 1 and 6 when phase 1 terminates and the third is from phase pair 2 and 5 when phase 5 terminates. Phase pair 2 and 6 is the only phase pair able to cross the barrier and begin the process again on the other side of the barrier with phase pairs 3 and 7, 3 and 8, 4 and 7 and 4 and 8. Phase termination is handled differently by each system and will be discussed in the following sub-sections. Please note that there are changes to these valid phase pairs and their order of appearance based on whether leading or lagging left turns are used and other control parameters, such as split phasing.

4.3.2 Conventional Control Logic

Conventional signal control logic covers fixed time, basic coordinated and advanced coordinated actuated operation. Each operation method is detailed below. Each of the three conventional systems, fixed time, basic coordinated actuated and advanced coordinated actuated is compatible with time of day and traffic responsive based plan selection. The details of the two plan selection methods are also detailed below. This means that there are effectively six combinations of conventional signal control logic and plan selection available for evaluation.

Fixed Time

Fixed time logic terminates phases when the planned amount of green time has been served. This makes the logic simple and predictable. Fixed time control is the most classical signal control methodology. It has not appreciably changed from its earliest uses in mechanical timer driven signal control. In practice, it is common for there to be four to five timing plans used at an intersection over the course of a day. These plans generally represent a morning plan, mid-day plan and evening plan with one or two extra plans for peak period traffic, if needed.

Up to five plans are available in the application. Each plan has an associated pedestrian plan option for use when the phase 4 or phase 8 pedestrian movements would require more time than the time normally allocated to those phases. It is assumed that phases 2 and 6, as corridor phases, will generally have sufficient green time to cover their associated pedestrian movements.

In general, fixed timing plans have been well modeled. The Highway Capacity Manual (HCM) 2000 (TRB, 2000) provides methods for calculating timing plans and analyzing performance. The HCM 2000 method of creating timing plans is based on finding a cycle length that is suitable for the intersection and movement saturations. Details can be found in Chapter 16 of the HCM 2000. These equations can be used as the starting point for developing timing plans for time of day and traffic responsive control.

Basic Coordinated Actuated

Many of ODOT's intersections are currently operating with the W4IKS software on 170 controllers. Other corridors are using Voyage software on 2070 controllers, but have not had advanced features enabled, or are using plans directly translated from the previous W4IKS operated 170 system. While there are differences between the various basic actuated operations, they share sufficient similarities to be modeled as the same system at a planning level.

The specific control logic implemented in the application runs the coordinated phase pair (2 and 6) under fixed time operations and does not allow phases 2 or 6 to be omitted. Other phases are operated in a typical actuated manner where a minimum green time must elapse before the phase may be allowed to gap out and terminate or reach its maximum allowed green time and terminate. Phases 2 and 6 are allowed to stay green given no demand for other phases. In the application this behavior is called resting. Other phases may be ignored if there is no demand for them. This behavior is called omission in the application. To retain planned coordination, any excess time saved from other phases terminating early or being omitted is accumulated to the coordinated phases.

A final note about basic coordinated actuated behavior involves the gap out behavior. Under basic coordinated actuated operation gap out occurs when all lanes of an operating phase have a sufficiently large gap. This behavior is called simultaneous gap out, sometimes it is referred to as simgap. This gap out logic resets its countdown each time a vehicle passes over any monitored detector.

Advanced Coordinated Actuated

With ODOT's transition to Voyage software on 2070 controllers there is increased interest in exploring the impacts of various advanced features available in the new software. In general, the Voyage software operated 2070 running coordinated actuated plans behave similarly to basic coordinated actuated with phases being served until minimum green time has been served and then either gapping out or maxing out to terminate the phase.

The major differences between basic coordinated actuated and advanced coordinated actuated are that advanced coordinated actuated actuates the coordinated phases (2 and 6), uses lane by lane gap out and can assign time freed up by early termination to serving pedestrian phases. Actuating the coordinated phases has potential impacts on mainline progression which are often mitigated by increasing the minimum green time on the coordinated phases to limit the possibility of premature gap out.

Lane by lane gap out checks each lane (detector) of a movement for gaps. Once a lane has gapped out under lane by lane gap out, it does not reset. This means that each lane can use the same gap out parameters instead of needing a different gap out parameter for each movement to account for different loop placements and idiosyncrasies. Advanced coordinated actuated is also allowed to assign unused time to cover pedestrian calls for short phases which allows the advanced coordinated actuated control logic to have a chance of serving side street pedestrian calls without using an alternate pedestrian phasing plan.

Plan Selection

There are two common methods of timing plan selection, time of day based and traffic responsive (Koonce et al., 2008). Under time of day plan selection a timing plan (for fixed time or actuated control logic) is selected based on the current time of day. A given plan may be used multiple times per day and be used for extended periods. For example, plan 1 may be used from 7:00 AM to 8:30 AM and again from 9:30 AM to 11:00 AM. It should be noted that some fixed time operating systems completely lack detection and can only use time of day plan selection.

Traffic responsive plan selection uses a different selection principle. Instead of choosing a plan based on the time of day, traffic responsive plan selection uses representative detectors along the corridor to select the timing plan that will best serve current traffic conditions. Effectively, traffic responsive logic breaks down to a decision tree where thresholds are set for detectors or combinations of detectors. When a given set of thresholds are met, the system implements the timing plan set by the engineer for that set of conditions (Koonce et al., 2008).

There are two commonly used sets of thresholds, volume and V+KO (or VPlusKO). Volume is as simple as it sounds with each detector reporting its volume, typically in terms of vehicles per hour. V+KO stands for volume plus a constant, K, times occupancy, O. This method is preferred where congestion may cause reduced volumes or queues. For reduced volumes, congested detectors will report higher occupancy from slow or stopped vehicles, offsetting the reduced volume during congestion. For queues, an upstream detector that should be beyond normal queues will begin to register increased occupancy when traffic is no longer free flowing over the detector. The occupancy factor prevents the traffic responsive system from reverting to lower volume timing plans or ignoring queuing when congestion occurs and more service may be required (Koonce et al., 2008).

The process of selecting which plans should be used at a given time of day or which detectors and thresholds to use in a traffic responsive plan selection can require a significant time investment in corridor observation. In the application, the difficulties associated with selecting appropriate detectors and thresholds would be compounded by the differences between synthetic occupancy and a measured occupancy from the field. To avoid significant differences between modeled performance and performance expected from traffic responsive plan selection, the application does not currently implement V+KO. Instead the application uses a simple volume based approach. This implementation simplifies user input as well as calculation and programming logic. The application implementation selects one intersection to serve as the master intersection with phase 2 and phase 6 volumes at that intersection being used to determine the appropriate plan.

4.3.3 Adaptive Signal Control System

Adaptive signal control systems use custom and often proprietary logic to adjust their timing parameters to current traffic conditions. The three systems considered in this research are InSync, ACS Lite and SCATS. All three of these systems have proprietary algorithms that could not be implemented in the application. Instead, a series of basic adaptive control strategies have been created that are based on plain English descriptions of how each system works. These surrogate systems are named for their method of operation. Delay optimization was created based on InSync's described operating principles. Slow occupancy emulates ACS Lite and fast occupancy imitates SCATS. For convenience and clarity the various algorithms are also indicated by the name of the intended system preceded by the word faux to indicate that the implementation is not a direct implementation of the proprietary algorithm.

Delay Optimization (Faux InSync)

The two core principles upon which InSync operates are green band progression and delay minimization when a green band is not scheduled. InSync optimizes delay across movements by counting approximately how many vehicles are present (using video detection) for each movement every five seconds and serving the movement group that has the most vehicle-seconds of delay (Rhythm Engineering, 2012). For example, one vehicle that waits fifteen seconds will accrue as much delay as three vehicles waiting for five seconds. An important consideration is that Insync is not required to operate in cycles with consistent phase order like conventional systems.

The delay optimization strategy can reasonably represent InSync's delay minimization logic for serving phases outside of green bands. These algorithms, while proprietary, are straightforward and well described. The algorithms by which InSync creates a green band, however, are not described nearly as well. A series of educated guesses and simplifications have been necessary to integrate green band logic into the application.

The green band logic, as implemented, checks the ends of the corridor and determines when the end intersections wish to discharge their coordinated through movements. When an end intersection discharges its through movement, a series of calculations are made to determine what the offsets are between intersections. Another calculation estimates the required size of the green band based upon the measured delay at the intersections and user input minimum and maximum tunnel sizes. The logic then requires that each intersection be serving the appropriate through phase at the appropriate time and continue to serve that movement until the green band time has been exhausted, upon which, the intersection operations revert to serving the phase with the most delay, which may be the coordinated through movement. To prevent numerous small green bands from causing the system to become unstable, green bands are required to be spaced at least the minimum tunnel green time apart.

As an example, a four intersection corridor would generate a green band in the increasing intersection number direction when intersection 1 wants to serve its phase 2. From this point intersection 2 will be required to serve phase 2 at a time in the future equal to the travel time from intersection 1 to intersection 2. Intersection 3 is required to serve phase 2 at a time in the future equal to the travel time from intersection 1 to intersection 3, and so on. The intersections would be required to serve phase 2 for a number of seconds equal to the minimum tunnel green time specified by the user and then they revert to serving whichever local phases have the greatest delay, which may include phase 2. After the green band has expired at intersection 1, no new green band can be initiated until the minimum tunnel time has elapsed.

Slow Occupancy (Faux ACS Lite)

The ACS Lite system uses time of day based plan selection system to select an actuated control plan as a base upon which to perform its adaptive control logic. Once a plan has been selected, the ACS Lite system adjusts the maximum green times every 5-15 minutes (*Gettman et al., 2006*). ACS Lite can adjust splits separately for each intersection. The system is biased in favor of coordinated phases to help maintain progression.

The ACS Lite split optimization plan is quite straightforward, with phase splits balanced based on green time utilization. The determination of green utilization is based on phase saturation, which is a measure easily derived from the queuing model. From this point it is relatively simple to determine which phases need more time and which phases should donate time based on their relative saturation levels. The system is only allowed to make small changes to the plan each interval, which keeps the system from becoming unstable due to overreaction.

The offset calculator is more troublesome and impractical to implement in Excel. The offset calculator uses statistical measures to identify whether vehicles are arriving at downstream intersections during green indications. This would require more tracking and calculations than are practical to implement under the limitations of Excel.

In the application, the phase split balancing methodology is implemented. Each 15 minute interval split adjustments are recalculated based on the previous 15 minutes worth of data. Offsets are maintained according to the original timing plan under the assumption that the offsets should not appreciably change based on differing splits within a fixed cycle length.

Fast Occupancy (Faux SCATS)

SCATS operates with two levels of control, tactical and strategic. Strategic control is focused on determining the correct cycle for a signal or group of signals. Tactical control looks to optimize the use of cycle time allocated by strategic control.

Strategic control focuses on cycle length and coordination. Cycle length is determined based on phase and intersection saturation. Coordination is created by observing the vehicle flows between intersections and uniting multiple systems under the same cycle length when those vehicle flows are high enough to warrant cooperative cycle lengths.

Tactical control allocates green time within a cycle. Phases may be terminated early based on low demand or skipped entirely when there is no requisite demand. Effectively tactical control acts as though the system was isolated with the exception that the coordinated phases cannot skip or terminate early, in order to maintain progression (*Roads and Traffic Authority, 2011*).

In the STATICS application, tactical control has been implemented according to the available plain English descriptions. Elements of strategic control, such as the logic to combine multiple intersections in a coordinated group and selecting appropriate cycle lengths, have been implemented. Once again it is the progression logic that is unavailable. A simplified progression logic has been implemented which chooses between increasing intersection direction progression, balanced progression and decreasing intersection number progression with linear scaling of offset values calculated accordingly.

4.4 Required Model Output Data

In order to perform the cost and benefit analysis to select the most appropriate systems to analyze in greater depth, certain performance measures must be output from the model and evaluation logic. These data include volumes, delay, queue lengths, number of stops and saturation.

Volumes are an important aspect of system performance to report. Volumes are an important tool for internal evaluation. Also certain performance indicators can be reported in different units for clarity and may require volume information to make the conversion. For example, the total delay and average delay can both be important measures of performance, but average delay requires knowing the number of vehicles delayed in order to calculate it.

Delay is another important measure of performance. Delay is also one of the performance aspects that is most visible to road users. Minimizing vehicle delay is a common optimization goal for traffic signal systems.

Queuing can lead to severe performance impacts as well as having safety implications. Queues that overflow left turn bays can put stopped vehicles in front of through movement traffic which may be flowing. This presents a collision hazard and is undesirable. Queuing from downstream intersections can prevent upstream intersections from operating well.

The average number of stops to traverse a corridor is a commonly used measure of performance that indicates how well progression is working on a corridor. Stops are another aspect of corridor performance that is readily apparent to road users.

Saturation is the final performance measure of interest for this research. When phases are under saturated, there is room to adjust phasing, timing or features used to reduce wasted time. Similarly, when phases are nearing or over saturated it may be necessary to adjust settings to add more time to the saturated phase.

Chapter 5: STATICS Cost-Benefit Analysis

One of the challenges faced by agencies selecting a new traffic signal control system is getting the best value for the money spent. This Cost to Benefit Analysis (CBA) can be based on many costs and consider numerous benefits. Typical benefits considered in the transportation field include travel time and vehicle costs such as fuel consumption (VTPI, 2009). Numerous studies have looked at savings in travel time or delay and fuel consumption, and converted them into dollar costs for comparisons, typically reported as savings over the previous system (DKS, 2008; Dutta and McAvoy, 2010; Gettman, et al., 2006). It can be surprising how rarely those same studies indicate the costs incurred. Of the three studies listed previously, Dutta and McAvoy (2010) indicate that a total of $12 million was allocated between county and federal sources; Gettman, et al. (2006) indicate an expected system cost between $10,000 and $30,000 excluding infrastructure; and DKS (2008) breaks out the construction, design and integration, benefits evaluation, installation and annual costs.

There are a number of costs endemic to purchasing and installing a traffic signal control system. These costs range from the purchase of hardware such as controllers and communications equipment to licensing costs for controller and central system software. Often these costs are spelled out in purchasing contracts and are otherwise known in great detail. Also, agencies typically have supply contracts and a history of maintenance and installation projects that allow engineers to estimate equipment needs and costs.

There are other, less immediately visible, costs such as engineer and technician training that are often overlooked in the published reports. These costs can sometimes be troublesome to quantify depending on the agency's record keeping. With short funds and restricted hiring at many agencies, labor hours for planning, installation, project oversight and operations can no longer be excluded from cost considerations. This is especially true when staff levels play into the objectives and goals of implementing the traffic signal control system such as in Gresham, OR (DKS, 2008).

One of the key aspects of CBA analysis is valuing the various costs and benefits in a common measure for comparison, with money typically used as the common measure. When costs are then compared to benefits, a cost to benefit ratio can then be established for the comparison of multiple projects that may or may not have much in common. In this research, values are attached to performance measures which are then used to calculate a cost to benefit ratio for users to apply to comparisons between systems. Because the values attached to numerous measures can change over time, the research team has made these values changeable by the end user. For example, the value of time spent waiting in a queue would be expected to vary by prevailing wage in the area. Likewise, a new union contract could change the valuation of a technician's time spent installing equipment.

The system feature and selection process envisioned by STATICS involves inputting the system parameters and selecting advanced features for each candidate systems or feature combination and running STATICS to generate estimates of performance to be used in the CBA. After the CBA it is up to engineers and managers to determine whether to pursue a given course of action. One concern expressed by ODOT personnel during the development of STATICS was that a blanket recommendation of any given course of action may cause rifts between engineers and management based upon the consideration or lack of consideration for factors or combinations of factors. Because of this concern STATICS is not designed to directly recommend a given course of action, but instead, to aid engineers in narrowing options by eliminating the most flawed options and help them identify the total cost and expected benefit of a given signals project.

5.1 Benefit Calculation

The cost to benefit ratio analysis methodology in STATICS is built upon a series of models. The analysis builds upon the models introduced in Chapter 3, which are a queuing model to estimate delay, queue length and other performance measures; a logical model to represent intersection and segment configurations; and, from Chapter 4, a signal control model to implement the various signal control strategies. The interaction of each of these models with input data produces the performance estimates used to generate expected benefits.

5.2 Benefit Valuation

Like transportation agencies, there are two costs that matter to roadway users, time and money. One principle difference between user and agencies though, is that an individual user's time is spent in small chunks. This means that while time spent in traffic can be correlated to many stress indicators and frustration (Stokols, et al., 1978); it can be difficult for users to see changes in lost time. Consider an average travel time savings of ten seconds over a two minute average trip. Now, consider the variability in the trip duration when individual trips can vary by over thirty seconds just by getting one more red light. Unless travel time savings are significant, it can be difficult for road users to notice improvements while experiencing natural variation.

Because an agency cannot directly show increases in productivity due to reduced delay and it is difficult to show substantial individual time savings, it is typical for agencies to use a time value of money to put a value on the aggregate user time saved by a signal control system improvement (DKS, 2008; Dutta and McAvoy, 2010; Gettman, et al., 2006). Users and agencies are also showing increasing interest in travel time reliability and users are willing to pay for it on the freeways (Brownstone and Small, 2005).

Obviously time is not the only cost to users, they must pay for fuel and vehicle costs as well. The benefit gained by installing a new control system is defined as the benefit difference between the new system and the original system:

$$B = \sum B_n - \sum B_o \quad (5\text{-}1)$$

Where $\sum B_n$ and $\sum B_o$ are the total benefits, valued in dollars, for the new control system and original system.

While it is easy to represent the total benefits in mathematical terms, it can be more difficult to value individual benefits. For example, how should travel time reliability on arterials be measured? Is the 85th percentile an appropriate choice? Or, should standard deviation be used? How should reliability be valued compare to average travel time? For freeway based work, these questions have a rapidly maturing body of research attempting to answer the questions (Brownstone and Small, 2005; Texas Transportation Institute and Cambridge Systematics, 2006). Work on arterial travel time reliability focuses on measures such as the buffer index, a measure of the difference between an average trip and the 95th percentile travel times (Texas Transportation Institute and Cambridge Systematics, 2006). Data such as the buffer index can be calculated using the average travel times and the 95th percentile of travel times generated during MCM calculation.

Environmental benefit valuations are a current field of inquiry that shows promise for inclusion into the STATICS evaluation process. Some additional data collection during performance evaluation could easily collect data of use for emissions calculation such as time spent cruising, number of stops and stopped time. Future work on STATICS, incorporating the QACD model discussed in Chapter 6, can incorporate the collection of acceleration and deceleration as well as more diverse vehicle type data for use in more comprehensive environmental analysis.

5.3 Cost Analysis

One of ODOT's primary goals with regard to this research was to enable them to determine which corridors may be good candidates for adaptive signal control systems. This general goal can be broken down into three specific questions. The first question is, would a new signal control system provide a performance benefit to the corridor? The second is, would that performance benefit be worth the time and money needed to realize it? Finally, which signal control system provides the most benefit compared to the time and money needed to install it? These three questions are at the heart of the CBA framework developed by the research team.

One challenge that frequently came up in the CBA portion of STATICS is that public agencies have incredibly poor accounting practices when it comes to engineering time and resources expended on a given traffic signal control project. Over the course of the research, it became obvious that agencies do not know how much their traffic signal control system actually costs them because their budgeting practices divide the costs up in ways that can't easily be reconciled to a given project. For example, new systems or licenses for existing systems are typically purchased as part of a capital project building or refurbishing a corridor while engineer time to work on timing plans for that corridor is rolled into an existing budget item for retiming signals and technicians are not involved in the process because the contractor's technicians are doing the initial work. For the next year, the signal engineers do not need to work on the project because it has new timing plans and they are needed on other retiming work (under the same budget) and technicians perform routine maintenance as needed under their standard budget while the intersection licenses are rolled into the general renewal budget. In such an ideal case it may be possible to identify how much the new signals cost the DOT. However, in practice, the budgeting of time and money is not even that clean because time and hours are billed to budgets with money, not necessarily the correct budget. This problem was encountered at multiple agencies contacted to gather information about the costs of traffic signal control. Because of this the CBA portion of STATICS is designed to be flexible and accept user inputted values at many steps to allow the CBA process to more closely match the realities of agency cost estimation.

5.3.1 Cost Valuation

Money and time are the two resources that matter to agencies. The interest in monetary costs is straightforward and simple to understand. While the conversion of labor time into monetary costs is a simple matter of determining the costs of an employee's wages and benefits, there are more subtle issues related to costs that agencies may need to consider. Increasing or decreasing the number of employees an agency employs is not instantaneous and entails a large number of other costs that can be hidden or not directly tied to projects. Examples of costs that can be tied to increasing the number of employees include availability of office space, computers, rest rooms, training needs and more. Costs associated with reducing employee count can include unemployment insurance, administrative costs, severance packages, retraining/reassignment costs and a number of negative outcomes due to bad attitudes and behavior (Cascio, 1991). Table 5-1 summarizes some of the cost components related to implementing a signal control system broken out into engineering/tech costs, system costs, communication costs, and training costs categories.

Table 5-1: Cost Summary

Engineering/Tech Costs	**System Costs**	**Communications Costs**	**Training Costs**
Timing Plan Creation System Optimization Controller replacement Detector installation Detector validation Comm. Installation	Licenses Maintenance Hardware	Monthly Comm. Services Intersection Comm. Hardware Trenching (for Comm.)	Engineer training cost Technician training cost

While the potential costs surrounding employees are varied and may be difficult for agencies to pin down, hardware costs and software costs and construction costs are much more concrete. Agencies such as ODOT have personnel trained to estimate the costs of projects and write the contracts governing their construction and implementation. Likewise, frequently purchased equipment such as controllers and detector hardware are often procured under contract at negotiated rates. These factors make establishing a total cost for hardware, software and construction relatively straightforward.

To prevent confounding factors from influencing the results, the decision was made to focus cost estimation on the engineer and technician activities directly related to the signal control system. An important aspect of this decision is that restricting the personnel costing decisions to those activities and costs most directly related to the signal control system will limit differences in cost attribution and make costs more defensible and definable under contestation. Additionally, since the focus is on traffic signal control system costs and not construction costs, only hardware and software costs directly related to signal control are considered. Construction of and maintenance for additional right of way, lanes, illumination and other features that are commonly incorporated into corridor upgrades are explicitly ignored.

Training and staffing costs are important to consider. Depending on the particular details of the purchase agreement, training may or may not be included in the contract along with other costs, such as licensing. Regardless of how training is contracted or paid for it will have two costs that factor into the CBA. The first is direct costs of the training session such as the cost of having training staff present the training, facilities costs, equipment costs, etc. The other major cost is in engineer and technician time. A day of training, even if the session is considered free or incorporated into the purchasing contract, will still cause a day of lost productivity for the engineering and technician staff, and their respective hours should be accounted as a cost in the CBA.

5.3.2 Cost Estimation

The total cost for implementing a control system is the sum of the cost for engineering/tech costs, system costs, communication costs, and training costs. That is

$$C_{total} = \sum_{i=1}^{n} \beta_i T_i + C_{sy} + C_{com} + C_{tr} \qquad (5\text{-}2)$$

Where β_i and T_i are the hourly rate and hours for the i^{th} kinds of work, respectively; n is the total kinds of work considered in the engineering/tech costs; C_{sy}, C_{com}, andC_{tr} are the system costs, communication costs, and training costs, respectively.

It is important to note that the costs associated with each category have temporal and spatial variability. Work done today in Portland, OR will have different cost values than work done in Bend, OR ten years from now. This can be due to a number of factors, such as inflation, availability of contractors, expertise of personnel, etc. Because of the variable nature of the individual components of engineering, technician, system, communications and training costs, these data must be supplied by the user when performing the evaluation in order to produce accurate results.

5.4 Cost to Benefit Ratio Calculation

The end goal of a CBA is to determine the ratio of benefits to cost for each system being considered. The benefit-cost ratio (BCR) is often used for comparing different systems or projects to determine which projects have the highest positive impacts relative to their costs. The BCR is defined as the ratio between the total benefits and the total costs (Shively, 2012):

$$BCR = \frac{B_n - B_o}{C_n - C_o} \quad (5\text{-}3)$$

Where B_n and B_o are the total benefits in dollars for the new control system and original system; and C_n and C_o are the total costs in dollars for the new control system and original system.

It is important to note that the BCR is not a requirement that a specific project or system be funded. It is a decision making aid that will help choose between systems, but it cannot consider all of the factors involved. For example, it is possible for a system to have unacceptable performance in one or more areas, while still providing enough performance increases in other areas to generate a high BCR. Selecting such a system for implementation would be problematic, thus BCR cannot be used as the sole criteria in system selection. Engineering judgment will still be needed to determine if all aspects of the system and its performance will satisfy the needs and demands of the corridor. Likewise, performance benefits are meaningless if the total cost of the system is beyond the reach of the funding agency. One of the main purposes of the BCR is to get practitioners to consciously consider total system costs, particularly those like training and licensing costs that are typically accounted to other budgets.

5.5 System and Feature Selection

One of the major goals of STATICS development was to create a tool that could examine a corridor at the planning level and estimate which features or systems might be beneficial to implement on that corridor. Given the aspects of hardware, software and labor considered in the cost analysis, it is expected that implementing advanced features on an existing system would be more cost effective than implementing a new system in most cases. While this result would seem to be obvious and nearing tautological, it is not the default state of the practice. The FHWA has implemented the System Engineering (SE) process and introduced model documents (FHWA, 2012) for users to implement the process, which is now required for federal funding of traffic signal control projects. The FHWA began requiring the SE process, which includes checking if advanced features of the existing system ameliorate the observed traffic problems, after multiple adaptive traffic signal control projects they funded were shut down for not meeting performance expectations. Now they want applicants to examine and test, if appropriate, unused advanced features in their existing systems before buying new systems.

Chapter 6: QACD Model Methodology

During the development of the queuing model for the STATICS system a number of ideas were pursued that turned out to be too complex for implementation in Microsoft Excel. Rather than discarding these ideas, a new mesoscopic model was assembled from the best of the ideas. This model was designed under the constraints that it would be implementable on simple hardware, such as current traffic signal control hardware.

The purpose for developing such a model is to help address challenges such as traffic signal optimization. This is a very challenging prospect because signal control systems in general are constrained to looking at data from the present and the past. Specifically, until vehicles pass a sensor, the system has no knowledge of them. There are two solutions in practice. One is to place sensors far enough upstream to allow their data to be used to predict future traffic conditions at the intersection. The majority of current systems operate this way. The other solution is to create a network model to interconnect data from different intersections so that vehicle arrivals at downstream intersections may be predicted.

These two solutions have different strengths and weaknesses. Placing sensors upstream of a given intersection is a straightforward design and installation problem. Specifically, how far upstream is far enough and is traffic consistent enough between the sensors to allow the upstream sensor's data to predict traffic at the downstream sensor. These questions can be complicated by intersection spacing, driveways and on street parking. Essentially, the upstream sensor option is constrained by intersection spacing and the degree of exchange of traffic between the upstream and downstream sensors.

The model option is interesting for a number of reasons. First, a model option can use input from multiple sources to generate information relevant to a device's current location. Possible uses include mid-block pedestrian crossings looking for gaps in inbound traffic to minimize delay and a number of temporary and mobile applications. Second, a model can more easily accommodate erroneous data by looking at complementary detector inputs. Given detectors at the stop bars and exiting links of an intersection, each vehicle is detected twice, once at the stop bar and again at the exit. Some very simple applications of conservation of vehicles shows that the volume of vehicles passing a stop bar is equal to the number of vehicles passing the exit detectors with a little bit of time shift due to travel time crossing the intersection.

6.1 Model Time Horizon

The next considerations are implementation related. Specifically, questions such as how far into the future is it reasonable to model, how many intersections is it reasonable to predict across and how the model can handle a lack of input? Modeling traffic conditions too far into the future is problematic on practical and theoretical grounds. Predicting too far into the future involves processing increasing volumes of sensor and intersection data. This problem expands quickly as the prediction horizon increases. This is problematic given the stated goal of developing a computationally lightweight model for implementation on limited hardware, such as signal controllers.

If a grid of four-legged intersections with 10 second travel times between intersections is considered, a prediction horizon of up to 10 seconds would result in considering data inputs and state information from an intersection and its 4 closest neighbors. Expanding the time horizon to 20 seconds would result in the need to consider 13 intersections worth of data. In this situation modeling 30 seconds into the future would bring the total intersections considered up to 25. Figure 6-1 shows how the number of intersections considered increases with prediction time horizon.

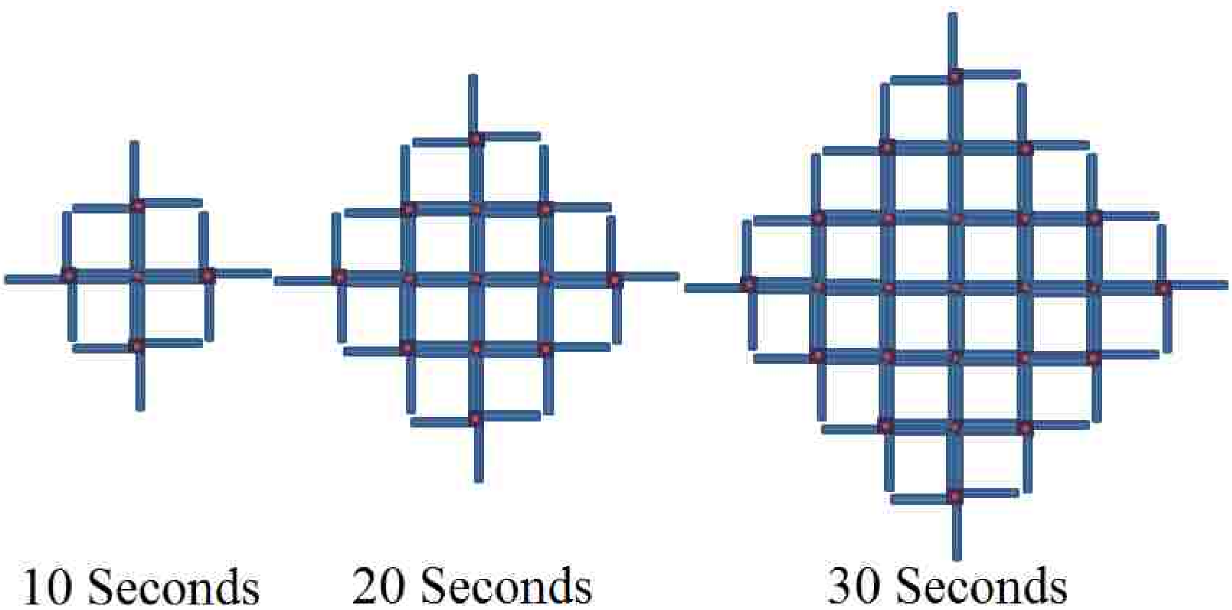


Figure 6-1: Intersections Considered By Model

The second question revolves around assumptions and the reality of predicting traffic conditions across an intersection. With current technology and practice, specifically, the lack of connected vehicle deployment, it is difficult to track individual vehicles accurately. This introduces a number of complicating factors to predicting traffic conditions across intersections. Something as simple as a free right turn or permitted left turn can cause significant errors in traffic prediction due to their uncontrolled nature. As the number of intersections considered expands, small errors in modeling intersection performance and random errors can be expected to accumulate.

Handling missing input data and intersections on the outer edge of the model where there is no upstream intersection to gather data from, introduces another challenge. In this case though, there are some useful behaviors to base a solution on. A traffic queue can be expected to dissipate at a saturated rate. This allows a model to determine if an input stream on an outer intersection has completely dissipated by looking for a break in the discharge flow rate. By calculating the number of queued vehicles over time, an arrival rate can be calculated.

When all of these factors are considered, a time horizon has been selected a priori to minimize errors. A secondary system design goal is to make the model and signal control system deployable on limited hardware and with limited communications, such as existing traffic signal controllers in the field. Both the expected error rates and implementation goals argue for a smaller time horizon. For this study a time horizon of 10 seconds is used.

6.2 QACD Model Design

There are more considerations to model development than just the time horizon over which the model will attempt to predict traffic flow. The model must also be able to reflect traffic conditions. To do this a mesoscopic model incorporating some elements of microscopic simulation and macroscopic modeling is proposed. This model will track individual vehicles so that future expansions of the model and, by extension, the signal system, will be able to incorporate connected vehicle data.

Inspiration for the QACD model comes from the work done on STATICS. Where the model underlying STATICS is primarily a queuing model adapted to Microsoft Excel, the QACD model takes advantage of having access to computer programming data structures to grow beyond a simple queuing model. Inspiration was also drawn from Daganzo's CTM (1994, 1995).

The QACD model improves upon queuing and cell transmission models by incorporating many more non-linear and individual vehicle factors. Improvements from queuing models include accounting for individual vehicle traits and addressing individual vehicles' travel from one intersection to the next. While the CTM can track individual vehicles in an aggregate sense, counting the number of vehicles in a given cell and noting when vehicles advance from cell to cell, information about a specific vehicle is not tracked. This ability to track individual vehicles and their relevant data through the model does not exist in the CTM or queuing models.

This model operates on a combination of queuing and microscopic simulation principles. Specifically, the model assumes vehicles are in one of four states, queued, accelerating, cruising, or deceleration. The model is named QACD after these four states. In this model a vehicle enters a link at cruising speed and travels at that speed until it closes with a leading vehicle or a yellow or red traffic signal. When the vehicle approaches a leading vehicle, it will enter the deceleration state and decelerate to avoid a collision or running a red light. If the vehicle slows to a stop, it will enter the queued state until the leading vehicle changes its state to accelerating or it receives a green light. Vehicles in the accelerating state accelerate until they reach cruising speed.

The QACD model is intended to be able to accept additional connected vehicle data when it becomes available, but function without it. To this end it is constructed to be able to track individual vehicles and track vehicle specific traits, even if those features are not implemented or used in the current modeling for SIBASS support.

The QACD model is composed of five entities, links, intersections, signals, inputs and vehicles as seen in Figure 6-2. Links are the segments between intersections; they have length, lanes, a free flow speed, and other geometric considerations. Intersections are the connection points between segments and store the connection information that allows vehicles to traverse from one link to the next as well as geometric data associated with the intersection. Signal data stores timing parameters and signal state information. Signals are tied to intersection objects on a one to one basis. Inputs are used when there is not an upstream intersection to draw data from. Inputs are tied to link objects where upstream intersection data is not available. The final object type is vehicles. Vehicles are containers for vehicle specific information, such as vehicle position, speed and state.

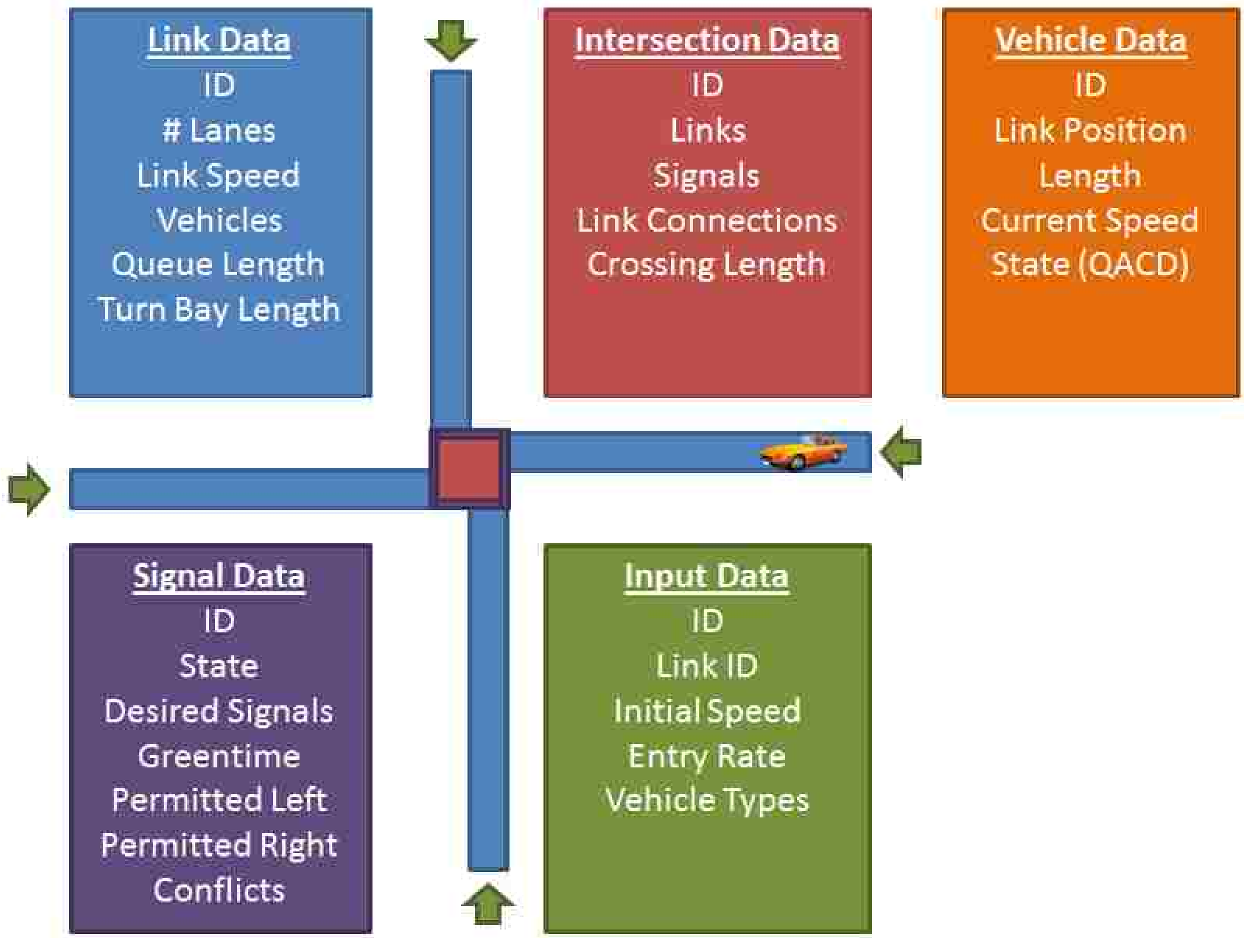


Figure 6-2: QACD Model Entities

Each second the QACD checks vehicle and signal states, then advances vehicles and signal states by one second. This process is shown in Figure 6-3. It begins with updating each vehicle's state. The signal control system relevant signal and link data are then output for external traffic signal control system evaluation. Inputs are estimated based on the signal states and link data. After the data has been output, signal states are updated to the previously determined next signal state. Vehicle positions are then updated to reflect their travel during the time interval. New input parameters are then received as is the next signal state.

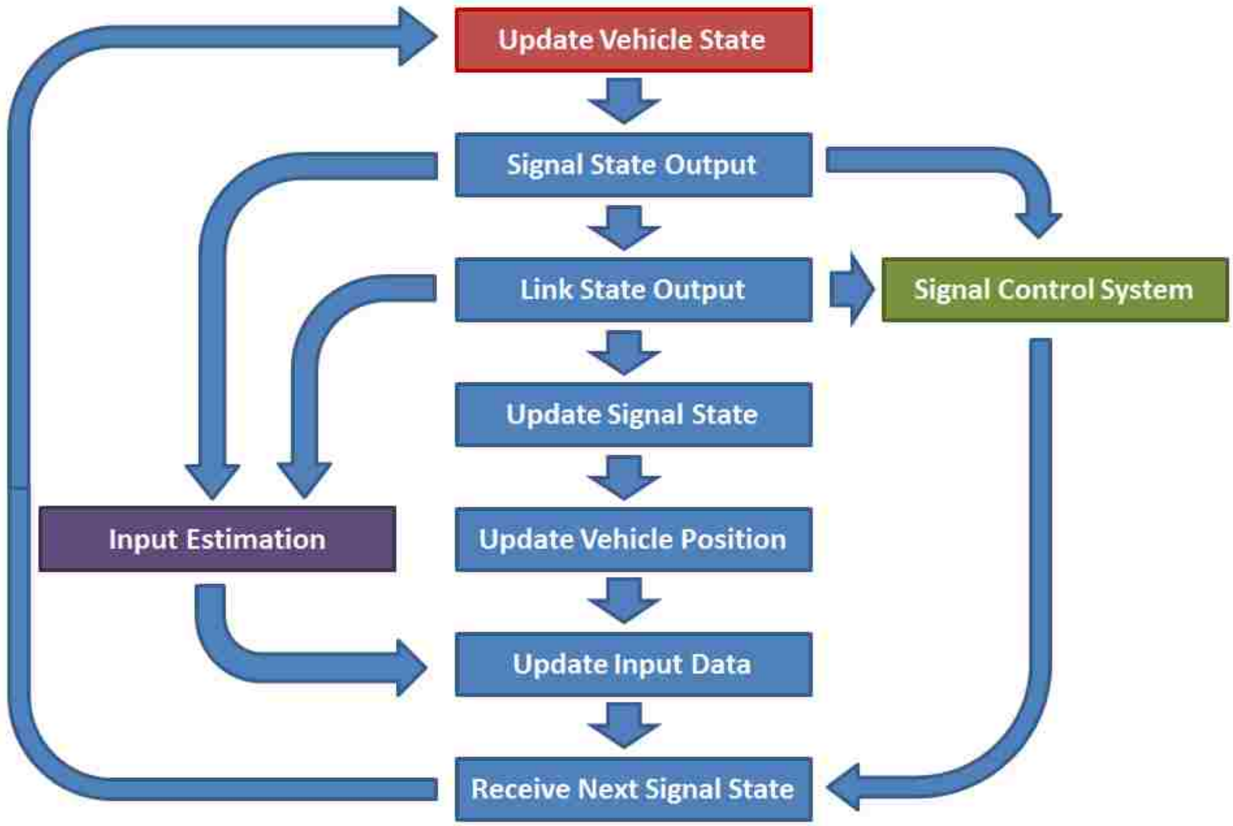


Figure 6-3: QACD Model Flow Chart

In Figure 6-3 there are three boxes that are colored differently. The first is "Update Vehicle State". This process uses average parameters for acceleration, deceleration and cruising speed currently. With connected vehicle data, vehicle state can be determined directly rather than using observed average behavior. The second box, "Signal Control System", represents external control of the traffic signal control system. It represents the control logic that translates input parameters from the current signal state and link states into a new traffic signal control state for the next time step. The third box, "Input Estimation", deals with the process of estimating inputs from uncontrolled inputs as opposed to vehicles travelling downstream through an upstream intersection.

Figure 6-4 shows how vehicles change their QACD state from queued to accelerating, accelerating to cruising, and so on. In the interest of clarity a number of conditions have been collapsed into “obstructions”. An obstruction is a yellow light with time and distance to stop, a leading vehicle traveling slower than the current vehicle within stopping distance or a queued (stopped) vehicle. A queued vehicle at the front of a queue (i.e. unobstructed) will change to the acceleration state when the appropriate traffic signal is green or an appropriate gap is available for permitted turns. An accelerating vehicle will change state to cruising when it reaches its desired speed. If an accelerating vehicle encounters an obstruction or red light it will convert to the deceleration state. A cruising vehicle will maintain its speed until it encounters a higher speed limit, where it will change state to acceleration, or it encounters a red light or obstruction, which will cause it to enter the deceleration state. A decelerating vehicle will enter the queued state if it stops or the acceleration state if the obstruction clears or light turns green.

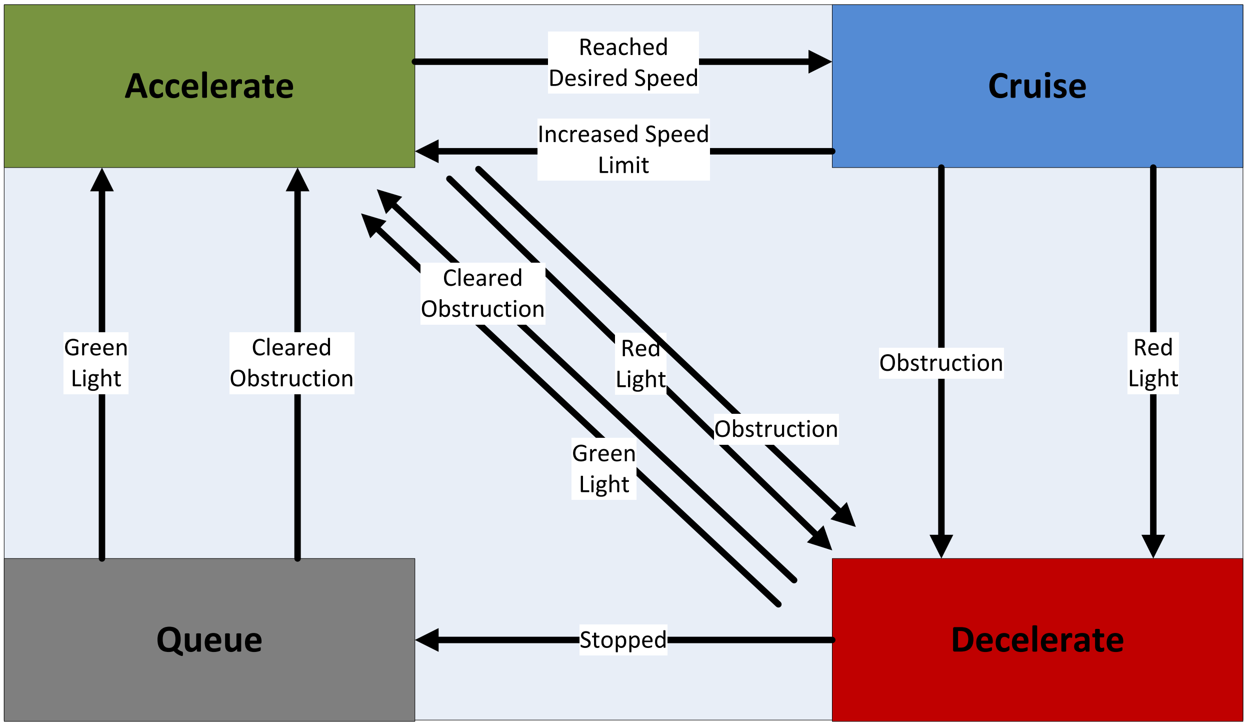


Figure 6-4: QACD Vehicle State Changes

6.2.1 Input Data

QACD model input data can be divided into several categories. The first is network data, such as how many links and intersections there are and what their configurations are. The second is starting input parameters. Vehicle related data, such as cruising speed and turn rates form a third class of input data. Finally, signal control data such as phase states, detector locations and permitted turns round out the QACD model input data.

Network data inputs for QACD are required to define a network topology to track vehicles and gather relevant data. Each intersection in the network is defined by an ID and which links are connected to it. Intersections also connect to signal control objects which carry the relevant phase states and timing information. Intersection objects also host performance measures gathered at the link and signal levels.

Links have basic parameters such as length and number of lanes. They also include additional geometric data such as the size of their left and right turn bays. Important signal control features, like detector location are also associated with link objects. Turn rates are associated with the link as well, though individual vehicles execute the turn logic. Finally, vehicle objects are added to collections associated with link objects indicating which vehicles are currently on a given link.

Input parameters are relatively straightforward. Inputs were designed to input vehicles when no other data was available. To this end they simply add vehicles at a constant rate as determined by initial conditions and modified overtime based on observed behavior.

Vehicle objects are defined by their position, state, acceleration and deceleration. Position is dependent on progress through the network and state begins as cruising, leaving acceleration and deceleration as input parameters. When vehicle objects reach a new segment they are randomly assigned to turning movements based on the current link turn rates.

Signal control related input data includes conflicting phases, detector locations, and starting signal states. Many of the operational characteristics of the signal control systems are external to the QACD model. They are necessary for various signal control systems to operate, but not part of the operation of the QACD model which passes information to an external signal control logic and accepts signal control input from the external logic to operate its signals.

6.2.2 Output Data

The QACD model is designed to output many useful Measures Of Effectiveness (MOEs) that will aid researchers and practitioners in operating and evaluating traffic signal system performance. The FHWA Traffic Signal Timing Manual (2008B) details the state of the practice regarding fixed and actuated control signal timing. The FHWA notes that MOEs can be used differently based on conditions. For example, during unsaturated conditions delay and stops are common performance measures. When conditions become saturated, the focus can change to queue lengths, cycle failures and percent time congested.

All of these MOEs can be gathered via a microsimulation model, provided one exists. However, the cost and expertise needed to develop, calibrate and maintain a microsimulation model puts microsimulation out of the reach of many agencies and researchers. The QACD model has been deliberately designed as simply as possible to make it available and implementable. The QACD model design enables many common MOEs to be gathered quite easily. It also enables some normally difficult to collect MOEs to be gathered. The method of gathering many of the MOEs is simply to sum up the number of vehicles meeting a certain set of criteria.

For example, the number of stops is simply a sum of vehicles changing to the queued state from any other state. Collecting delay data for output is a simple matter of iterating through vehicles on a link and counting the number of queued vehicles each time step. These vehicles can be allocated to movements based on where vehicles are queued on the link, specifically, whether a given vehicle is queued in a right or left turn lane.

Queuing is an important MOE and operational issue. Two queuing conditions are of interest. Queues that back from one intersection to the next will affect system performance. Queues that occlude turning lanes or back from turning lanes to through lanes have safety and operational implications. Queue measurement in the QACD model is a simple addition of vehicle lengths and a standstill distance allocated to through or turning lanes as appropriate.

What period data can be collected over is an entirely arbitrary matter for the QACD model. Most MOEs are expressed as sums that can be accumulated over whatever period is desired. This flexibility allows the model to accumulate data on whatever time scale is desired, from per second to per hour, or even per day.

6.3 Other Functions

As was briefly discussed, input objects are updated overtime to reflect changes in arrival rates. This process is relatively simple and straightforward. It begins with an initial value. This initial value is adjusted based on observed vehicle volumes every five minutes.

For SIBASS control, every five minutes the total volume of vehicles passing the detectors at the intersection is evaluated to determine how many vehicles arrived during that interval. Note that this is predicated on vehicles not experiencing cycle failures on the relevant approach so that accurate volumes may be gathered. In the event of congestion on that approach an estimation based on the percentage of time the approach experiences saturate flow is used. Specifically, if the approach is 100% saturated for all of the green time it is given, a larger arrival rate multiplier is used. This results in a longer estimated queue, higher estimated delay, etc. for signal control optimization purposes. When the congested approach begins clearing, the estimated arrival rate is reduced when the approach clears in the allotted green time. This is also the method SIBASS uses to estimate arrivals on uncontrolled approaches where no upstream data is available.

6.4 Future QACD Model Extensions

The QACD model is designed to be flexible and adapted as needed. This includes changes to the vehicle object design so that connected vehicle data can be integrated. Connected vehicle data offers solutions to a couple of problematic aspects of traffic modeling. First, having speed and acceleration data allows for increased accuracy. Second, connected vehicle routing information solves many of the inaccuracies inherent to random turn allocation.

Another interesting area to look at is modeling benefits based on passenger throughput. With an outside source of data, such as connected vehicle sensors or some other form of transponder that transmits passenger information, a whole new realm of modeling and optimization is possible. There are also opportunities to use the QACD model for economic purposes, with cargo types and/or values associated with the vehicle object.

While this initial development of the QACD model focused on passenger cars, it is obvious that there are more potential uses for the model. The next step in working with the model is to include pedestrians, mass transit and large trucks in the model. This would allow signal optimization to consider alternate optimization priorities such as per person delay, economic impact, etc.

Chapter 7: SIBASS

Experience during the construction of STATICS showed that each system had its own designated niche. Fixed time signal control works well under reliably saturated conditions and where closely spaced intersections mean progression between traffic signals is more important to travel time than the delay at an individual intersection. Actuated control tends to do well when arrivals are light and intersections are isolated from one another.

The adaptive traffic signal control logics also have their best use cases. InSync was designed for corridor operations and creates green bands between intersections on a corridor that minimize main street delay. During STATICS development, InSync was limited in its ability to operate on networks because green bands could only be created along the length of a corridor. SCATS was designed to operate under heavy traffic conditions in Sydney's urban network and can generally perform well when moderately to heavily saturated. Under low traffic conditions ODOT found that linking SCATS intersections could be more problematic than leaving them single and operating as free actuated intersections. ACS Lite, while showing an improvement over conventional actuated systems, adapts very slowly to changing traffic conditions. Overall, each adaptive system studied for STATICS analysis has at least one major fault.

Rather than trying to make a single optimization scheme work for all conditions, a new system is proposed that will utilize multiple optimization methods under different conditions. When traffic is light, an optimization pattern for light traffic will be used. When traffic is heavier, a different optimization method will be used.

The Swarm Intelligence Based Adaptive Signal System (SIBASS) is designed to use simple logic and the QACD model to adaptively operate a signal system at the individual intersection level. SIBASS's architecture is very simple and flat with each intersection controller operating independently. The challenging part of the process is to develop self-optimizing units that will create optimization at the system level without central oversight.

7.1 Introduction

The idea of swarms of low intelligence and input devices providing a means of optimizing processes is not a new one. Swarm intelligence is a buzz word for cellular automata and a number of other titles (Beni, 2005). Much of the work on cellular automata is based on work by John Von Neumann. His 1966 book on automata, the *Theory of Self-Reproducing Automata*, included an insightful example comparing a vacuum tube based computer to the human brain. In this example the human brain is composed of simple automata, neurons, analogous to the computer's vacuum tubes. Individually, neither the neuron, nor the vacuum tube is capable of processing significant amounts of data. Von Neumann postulated that it is the cooperative and organized operation of massed individual units that achieves the functionality observed in the greater whole.

Robotics research looked to cellular robotics as a means of achieving versatility with agglomerations of simpler robots (Fukuda and Nakagawa, 1988). The Fukuda and Nakagawa formulation of cellular robotics is based on the flexibility of living cells with the robots being designed as a selection of modular cells to facilitate combinations as needed to perform tasks. An alternate formulation of cellular robotics put forward by Beni (1988) extended cellular automata to include the concept of asynchronicity and non-sequential interaction.

As the field matured, researchers began looking more to natural occurring automata, such as insects, particularly ants, bees and other colony insects. Beni (2005) noted that the switch in terms from cellular automata and cellular robotics to swarms reflected a practical difference in operation, rather than just a sexy new buzzword, though Beni did note that a new name would help the field. By Beni's definition a group of robots has a different inherent dynamic than a swarm of robots. The swarm has its own characteristics in addition to the characteristics of its individuals.

Beni (2005) also noted two characteristics of swarms that are relevant to traffic signal control. The first is that swarm systems are built of very simple components. In relation to robotics, a swarm robot has the benefit of being more mass producible and modular. The second characteristic is resistance to disruption. A complex system needs complex and redundant systems to survive disturbance. One benefit of a swarm system is that disruptions of individual units can be adapted to by other swarm units.

One of the challenges in working with swarm intelligence is coming up with an acceptable definition of intelligence that fits a swarm. Beni (2005) developed a concise and straightforward definition: "Intelligent swarm: a group of non-intelligent robots ("machines") capable of universal material computation." In this definition a robot has been previous defined as capable of both information and material processing and a machine is capable of processing and/or transferring matter and/or energy. In this definition universal material computation includes the transferring or processing of information, energy and material in meaningfully ordered ways.

In this case, a traffic signal controller qualifies under both definitions. It processes information in the form of detector inputs and affects the transference of vehicles from one intersection to the next via right of way allocation as green time for various movements. This definition also fits SIBASS's application of swarm intelligence to ATSC. Under SIBASS individual traffic signal controllers are simple machines and the goal of SIBASS is to have those machines perform logical operations such as progression, minimization of delay, etc.

7.2 Phasing Selection

One challenge inherent to traffic signal control is phasing. For many reasons not directly related to signal optimization, traffic signals generally operate with the same phasing all the time. That is, they operate with the highest level of phasing needed during the day at all times of day. This can lead to some significant inefficiencies when, for example, protected-only left turn phasing is used during light traffic conditions that would allow permitted left turn phasing to be applied safely.

In many systems a phasing feature such as permitted left turn may be turned on or off by time of day or by traffic responsive plan selection. The ability of these systems to respond quickly and appropriately is the problem. If it takes more than 15 minutes to recognize conditions appropriate to changing phasing and cycle parameters and additional time to enact the changes, then the system will miss many opportunities for phasing optimization and may react to conditions that have already dissipated.

Intersection phasing is primarily a matter of left turns and directionality of traffic. In the trivial case, when left turns are prohibited, only two phases are needed, one to serve all main street movements and one for all side street movements. This is because through movements and right turning movements on the same street do not conflict, allowing all of them to be served concurrently and green time to be allocated between main street and side street based on the needs of the highest volume movements of each road.

As left turn volumes increase from zero, phasing requirements become more complex. When left turn volumes are low and there are sufficient gaps in oncoming traffic, permitted only left turn phasing may be used. As left turn volumes increase and/or gaps in oncoming traffic decrease, protected left turn phases need to be considered as separate entities for optimization purposes. At high ratios of left turn demand to available gaps in oncoming traffic, it makes sense to serve left turns only during protected phases for safety reasons.

Bonneson and Fontaine (2001) published an engineering study guide that includes guidelines for selecting permitted only, protected/permitted and protected-only left turn phasing. Trying to cross more than three lanes of oncoming traffic can lead to line of sight issues requiring protected only left turn phasing. Similarly, intersection geometries with two left turn lanes or intersecting left turn lines of travel need to be served with protected left turn phasing. Left turns with crossing lines of travel conflict with each other just as they do with the through movements.

In this case an even more restrictive phasing pattern is needed, one that enforces lead-lag operation with guaranteed service of through movements between left turn services to prevent left turning vehicles from colliding while trying to execute concurrent turns.

With proper rules and performance measures SIBASS has been designed to adjust the phasing used at an intersection based on Bonneson and Fontaine's work. Every five minutes SIBASS reevaluates an intersection's phasing. The primary factors of concern are directional ratios and the product of the through and left turn traffic volumes. The product of a left turn's volume and its opposing through movement volume is a proxy for the more complex interaction between left turn demand and gaps in the opposing through movement's flow. Directionality, the ratio of one approach's volume to its opposition's determines whether standard or split phasing should be used when protected phases are required.

In functional terms SIBASS selects a phasing scheme by first checking whether the left turns on the main or cross street have cross products exceeding the threshold value for permitted only operation. Bonneson and Fontaine (2001) used a peak hour cross product of 50,000 for a single left turn lane and opposing through lane and 100,000 for two or three through lanes to require protected and permitted or protected only phasing. For SIBASS operations, cross product totals have been converted for five minute volume intervals (350 for single and 700 for two or three through lanes) producing lower bound values for selecting protected/permitted operations. SIBASS uses a two threshold system to choose between permitted, protected/permitted and protected-only phasing. When the cross product exceeds the lower bound, protected/permitted phasing is used and when the upper bound (400/800) is exceeded protected-only phasing is used.

If one or both cross products exceed the permitted only threshold, then the intersection's phasing will increase in complexity. If either of the cross products exceeds the threshold to require protected only phasing, the complexity will increase again to include mandatory left turn phases. For the side street and main street the highest left turn phasing required is used. If the eastbound left and westbound through cross product indicated that protected only phasing should be used and the westbound left and eastbound through cross product indicated that permitted only phasing was allowed, then the east-west street would be phased for protected only left turns. SIBASS uses directionality in conjunction with left turn cross products to select a specific phasing scheme.

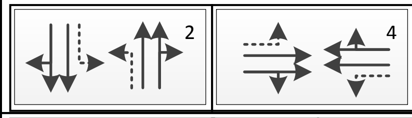
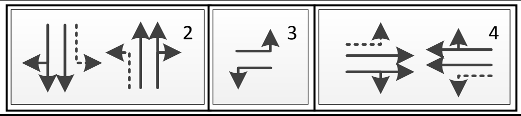
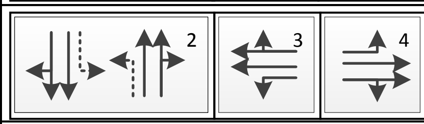
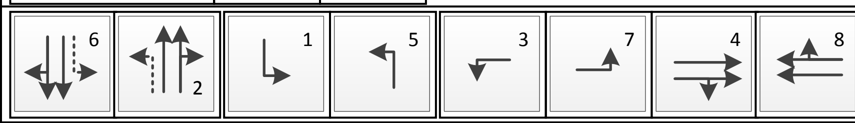
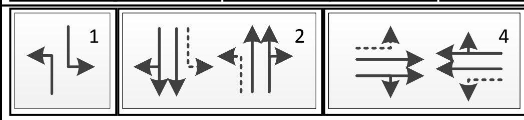
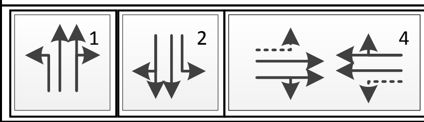
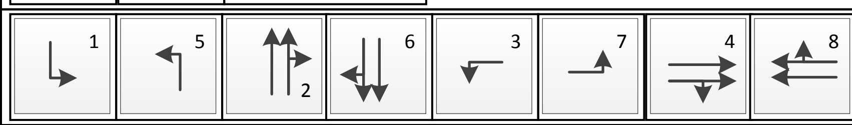
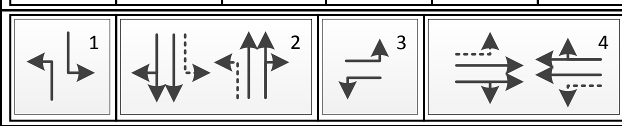
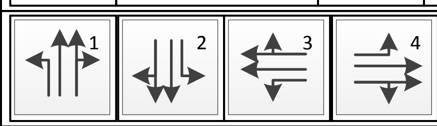
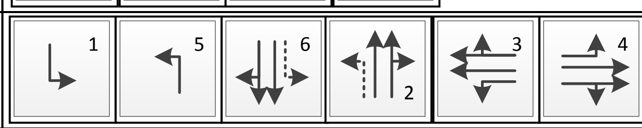
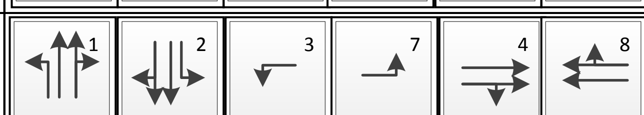
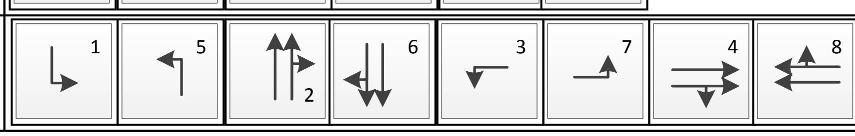
The difference between selecting split phasing is whether one or both approaches have sufficient directionality to justify split phasing in addition to protected/permitted left turns. When one approach's volume is more than 50% higher than the opposing approach's, split phasing is used. Note that split phasing fulfills protected left turn requirements and offers a low phasing option for high left turn conditions during relatively lighter traffic. Equation 7-1 shows how left turn requirements are assigned values between -1 and 2. These values are used in Table 7-1 to determine implemented phasing.

$$f(v) = \begin{cases} 0, v_L * v_T < X_{low} \\ \begin{cases} 1, X_{low} < v_L * v_T < X_{high} \\ -1, X_{low} < v_L * v_T < X_{high} \end{cases} \\ 2, v_L * v_T > X_{high} \end{cases}$$

(7-1)

Where V_L is the left turn volume and V_T is the opposing through volume associated with a given movement pair, phases 1 and 2, for example, X_{low} is the low cross product threshold for protected left turns and X_{high} is the high cross product threshold for protected left turns. The values 1 and -1 are used to differentiate split versus standard phasing. For example, when phases 2 and 5 have significantly more traffic (>50% difference) than phases 1 and 6 or vice versa, then *f(v)* will be -1. If the two directions have comparable volumes, *f(v)* will equal 1.

Table 7-1: SIBASS Phasings

N-S	E-W	Phases
0	0	
0	1	
0	-1	
0/1	2	
1	0	
-1	0	
2	0/1	
1	1	
-1	-1	
2	-1	
-1	2	
2	2	

7.3 Roles

The swarm intelligence aspect of SIBASS is based on the definition of a group of non-intelligent machines being capable of producing an ordered result. To achieve this each intersection movement is assigned a role in addition to its phasing. The roles are based on current traffic conditions. These roles determine the optimization parameters to be used in selecting phase service, relative priority in the case of ties and duration of green time allocated.

Figure 7-1 shows how the various roles built into SIBASS are intended to be selected. The Spinner role (in green) is designed for very low traffic operations where timely service makes queuing a negligible concern and most vehicles can be served without stopping. As arrivals increase, opposing vehicles become more likely to arrive simultaneously, making it implausible to serve arriving vehicles without stopping them. When traffic reaches this state, the Heavy Spinner role is used. Functionally, the Heavy Spinner role is analogous to an actuated control system with the ability to look at the QACD model and adjust its phase terminations in light of expected arrivals. The Congested and Metered roles are opposite sides of the same coin. When a link becomes congested and its queuing affects the upstream intersection, the Congested role is used at the downstream intersection and the Metered role is used at the upstream intersection. Finally, the Coordinator and Corridor roles are also paired. The Coordinator role is assumed by the most heavily saturated intersection that reaches Corridor status. When the Coordinator is selected, it calculates parameters needed for coordination and propagates them to the other Corridor role intersections.

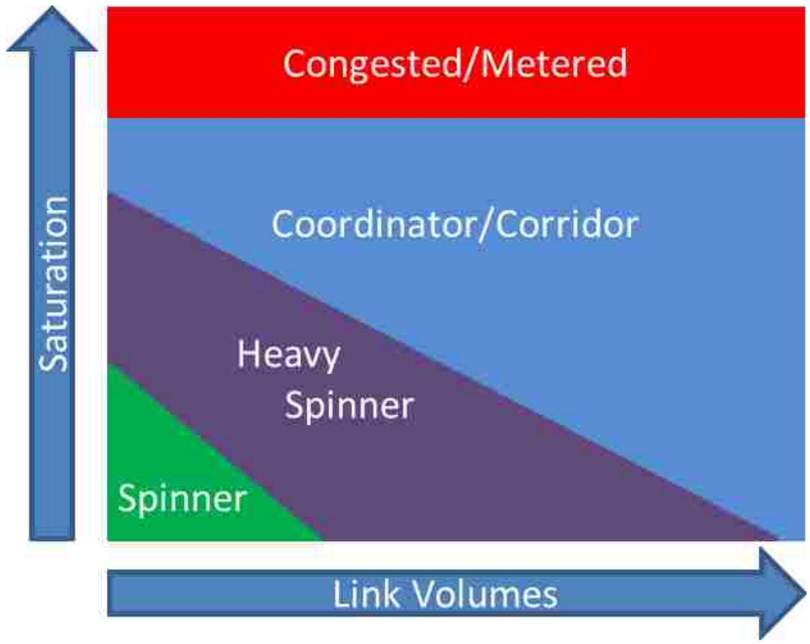


Figure 7-1: Applicability of SIBASS Roles to Traffic Conditions

7.3.1 Spinner

There are a number of roles built into SIBASS. The most basic and lowest priority role is the Spinner. The Spinner role is designed for low traffic conditions. The Spinner role weights its performance primarily based on minimizing stops and delay. The Spinner role has the lowest priority among the roles. Green time allocated under Spinner control begins at the minimum safe service time (default 5 seconds). The Spinner role is restricted to 4-phase or lower operation, though the conditions during which the Spinner role is selected effectively limit it to permitted only left turns and alternating green lights between the main and side streets.

Specifically, the Spinner role can be expected to begin suffering significant failures when the probability of arrivals not conflicting during a 5 second window falls below 50% as calculated using Equations 7-2.

$$P_{no\ conflict} = (1 - P_{T1})^5 * (1 - P_{T2})^5 * (1 - P_{L1})^5 * (1 - P_{L2})^5 * (1 - P_{not})^5 + P_0^5$$

(7-2)

Where vehicle arrivals are expressed in arrival rate per second, P_{T1}, P_{T2}, P_{L1}, and P_{L2}, for opposing through and left turn movements. The probability of a vehicle currently approaching the intersection on a concurrent phase is expressed as 1-P_{not}, where P_{not} is the probability that there are no concurrent phase arrivals and P_0 is the probability of no arrivals on any approach. The probabilities are raised to the fifth power to account for the time interval of five seconds. As an example, given 20 vehicles per 5 minute interval on each movement, the probability of zero conflicts is 12.6%.

The Spinner role's control logic may be found in Figure 7-2. Each time interval the Spinner checks to see if a vehicle is expected to arrive in the next 4 seconds (yellow plus all red time) on a conflicting phase. If there are no conflicting arrivals, the Spinner will rest in its current phase. If a vehicle is expected to arrive, the spinner checks for arrivals on the current phase(s). If no arrivals are expected for the current phase(s), the Spinner changes phases to serve the new arrival. If concurrent arrivals are expected, the Spinner checks to see if the opposing phases have experienced above a threshold level of delay. If the opposing traffic has been sufficiently delayed, the Spinner will change phases.

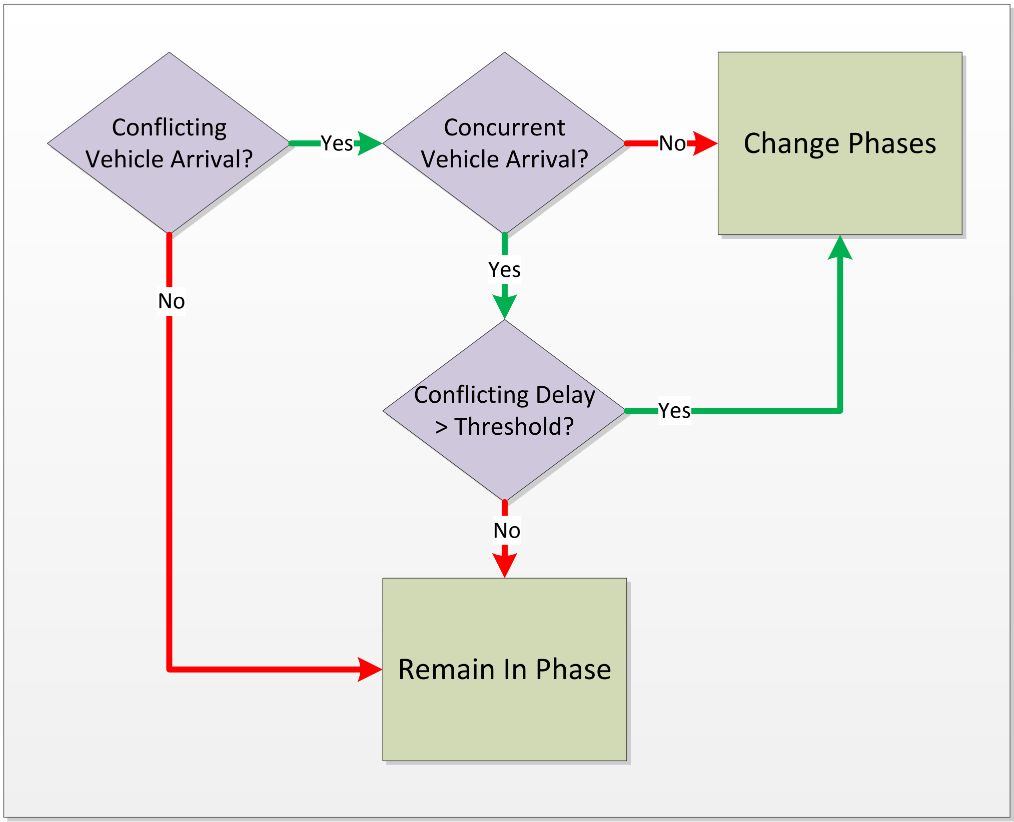


Figure 7-2: Spinner Control Logic

7.3.2 Heavy Spinner

The next SIBASS role is the Heavy Spinner, or just Heavy. The Heavy role is used when traffic conditions become heavier than the Spinner can easily serve. The Heavy role still seeks to minimize stops, but weights delay more heavily and includes projected queue length in its calculations. The Heavy role has a higher priority than the Spinner. The Heavy role begins with a higher minimum green time allocation proportional to the number of vehicles queued or expected to be queued by the time the queue clears divided by the saturation flow rate plus a few seconds to account for startup delay.

Figure 7-3 shows the Heavy Spinner control logic. When conflicting demand is detected and minimum green times have been served, the Heavy Spinner will compare measured objective function against the delay and stops it would incur terminating the current phase(s) to determine whether to change phase(s). If the objective function values for opposing phase(s) are not high enough to cut off the current phase(s), a second check is made to determine if queuing is becoming problematic, which will cause the Heavy Spinner to change phases.

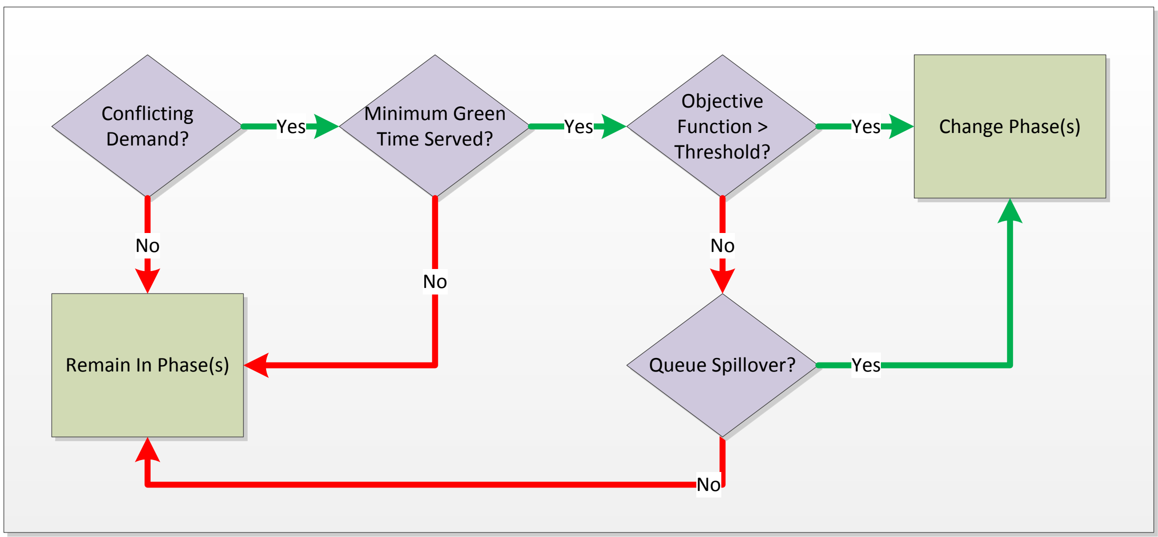


Figure 7-3: Heavy Spinner Control Logic

7.3.3 Coordinator

One of the primary means of reducing delay and stops is to employ coordination to allow platoons of vehicles to traverse multiple intersections without stopping. To achieve this behavior in a swarm system is quite a challenge. To accomplish this mission SIBASS uses the Coordinator role.

The Coordinator role is designed to ensure coordination with downstream intersections. The Coordinator role does this by determining a pseudocycle length based on the saturation of the various movements at the intersection. The Coordinator uses this pseudocycle to generate a sine function and offset, as seen in Figure 7-4. These values are propagated to the surrounding intersections as a means of creating coordination.

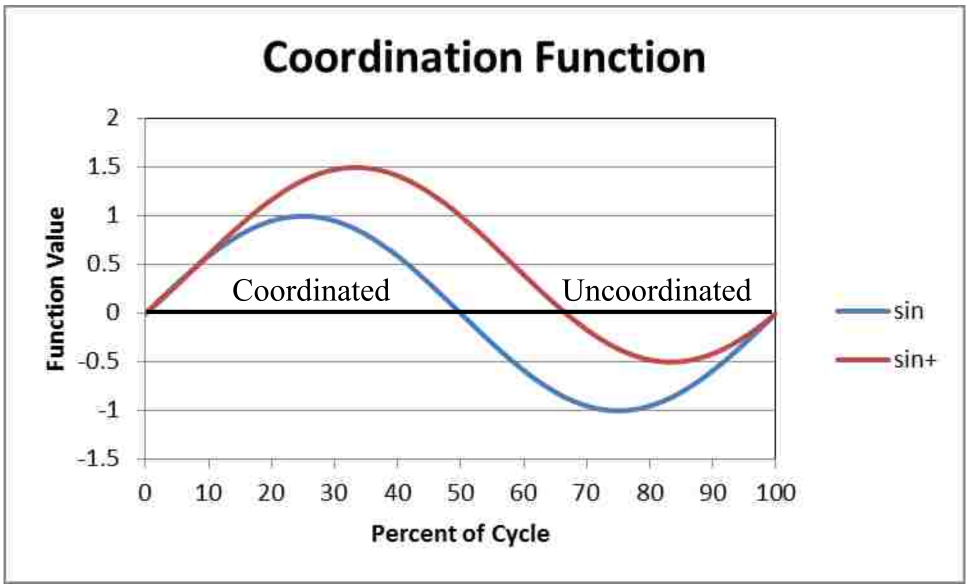


Figure 7-4: Coordination Function

The Coordinator role is designed to create progression. It does this by letting nearby intersections know when it will serve coordinated movements via the coordination function. By serving coordinated directions while the sine wave is positive and cross street movements while the sine wave is negative, the coordinator gives surrounding intersections enough information to create coordination.

The coordinator can serve north and south or east and west movements preferentially by shifting the sine wave up or down and adjusting the starting point so that each pseudocycle begins at zero, as seen in Equation 7-3. The psuedocycle is determined by θ which is equal to 360 divided by the pseudocycle length in seconds. The sine function value is shifted by y_0 up or down to bias the coordination function for either E/W or N/S service. This bias is limited to values between -0.75 and 0.75, which corresponds to a maximum of approximately 5:1 green time ratio in favor of the coordinated street. In order to have a continuous function a time offset t_0 is used to ensure that the function begins and ends at y=0 for each pseudocycle.

$$y = \sin(\theta t + t_0) + y_0 \tag{7-3}$$

The Coordinator role is expected to deal with more traffic than the Spinner and Heavy roles. This makes the Coordinator role much more likely to encounter situations where it can congest the downstream segment. To reduce the likelihood of downstream congestion, the Coordinator role allocates green time up to the available downstream link storage until the queue clears, when additional time can be allocated.

Figure 7-5 details the Coordinator and Corridor roles. Both roles use the coordination function to weight phasing selection in favor of the coordinated movements. However the Coordinator actually calculates the coordination function parameters rather than just using them. While the coordination function is positive coordinated phases are served if there is demand and other corridor movements are served if there is no demand. When the coordination function is negative, cross street traffic is served.

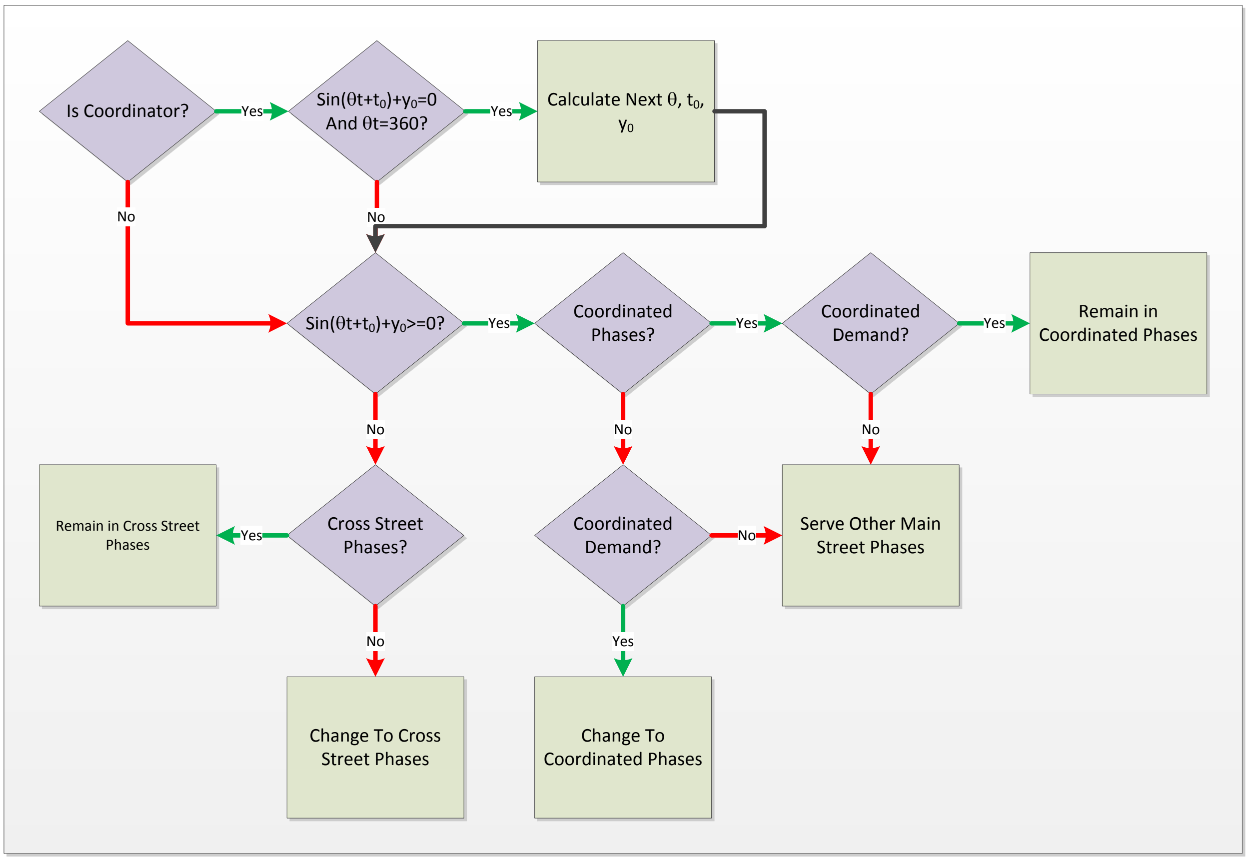


Figure 7-5: Coordinator and Corridor Control Logic

7.3.4 Corridor

The Corridor role is designed to work with Coordinators to produce progression between traffic signals. The Corridor role uses the sine wave produced by the Coordinator, combined with the known travel time between intersections to determine when to serve the coordinated movements. Corridors serve uncoordinated movements opportunistically between coordinated movement services.

The Corridor role is concerned with linear progression between Coordinator and Corridor role intersections. In this scenario a Coordinator produces the values used in Equation 7-3 and propagates them to the other intersections on the corridor. The Corridor intersections then calculate the objective functions for each movement, considering coordinated street stops, per movement delay and queues as normal with a final multiplier determined by the coordination function as seen in section 7.4. For the corridor movements the final multiplier is one plus the coordination function value while for cross streets it is one minus the coordination function with a minimum of zero in both cases. This makes the range of objective function multipliers from 0.0 to 2.75, strongly encouraging Corridor role intersections to serve coordinated movements at times that are compatible with the Coordinator intersection.

7.3.5 Congested

When a link becomes congested for more than a few seconds, two roles become relevant. The first is the Congested role and the second is the Meter role. The Congested role has the highest priority level of any service role and will be selected once a link becomes congested. This is intended to clear congestion as quickly as possible. The Congested role uses its high priority to serve the movement as frequently as possible. Green time is allocated based on saturated flow conditions. As the traffic flow becomes unsaturated, green time reaches max allowed service time or downstream link congests, the Congested role will cut off service and serve other movements. Figure 7-6 details the Congested role's control logic. The logic is simple and based on the assumption (built into the model and role design) that a heavily congested link will have a very high objective function value.

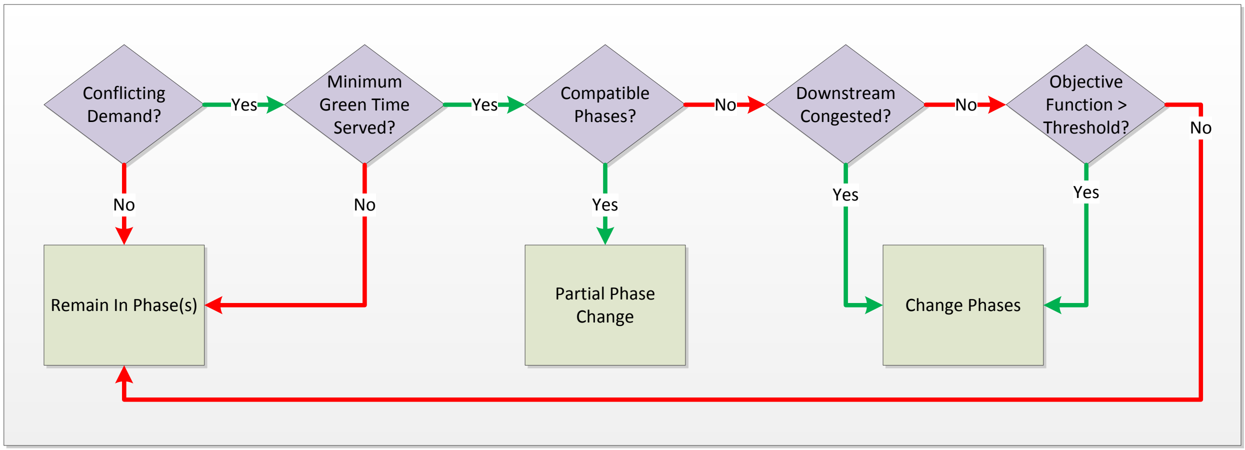


Figure 7-6: Congested Control Logic

7.3.6 Metered

The Metered role is at the other end of the congestion problem. If a link becomes congested enough to limit service at upstream intersections the intersections feeding that link will shift to the Metered role. The Metered role is designed to limit traffic entering a congested link. Specifically, it is intended to prevent the situation where traffic is given a green light but has no place to go because the downstream link is full, which wastes the time of everybody at the intersection. The Metered role allocates green time based on the available space on the downstream link. The Metered role has high or low priority based on whether space is available downstream. The Metered role is weighted more heavily when the downstream signal discharges vehicles and space is projected to open up at the end of the link. Figure 7-7 details the Metered role's control logic.

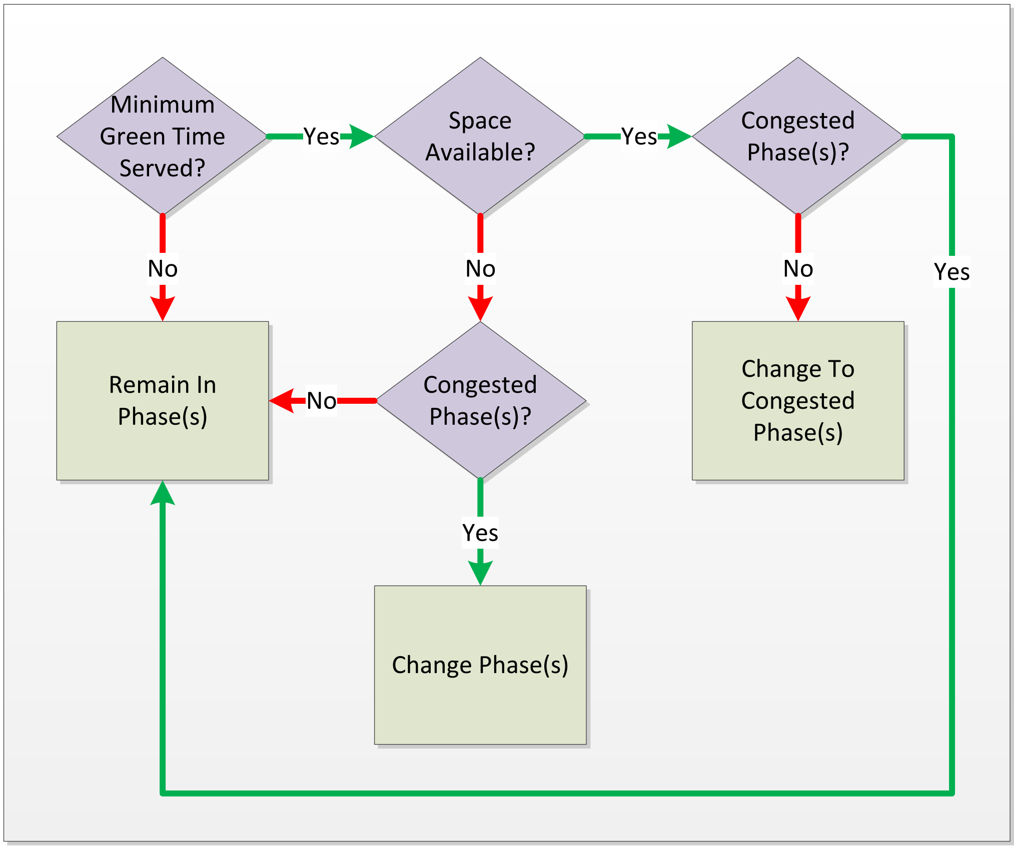


Figure 7-7: Metered Control Logic

7.4 Optimization Goals

SIBASS generally optimizes the selection of its next phases based on selecting the set of non-conflicting phases with the highest objective function values. With the objective functions and other control limits changing depending on the role assigned to each intersection, SIBASS changes its intersection optimizations to match current traffic needs. The plethora of possible combinations of intersection roles on a network or corridor makes the design of SIBASS very important. To operate effectively, two major design points need to be well addressed. The first is role stability. The second issue is having roles fill a contiguous and complete state space describing movement operational characteristics. In other words, for any combination of volume, saturation, queuing, etc. there should be a role designated to operate in that space as seen in Figure 7-1.

Rapid switching of roles over short time scales would cause optimization issues. Consider how chaotic the optimization might be if a given intersection were to switch between the Metered, Spinner, and Coordinator roles on a rapid basis. To prevent rapid role switching from causing issues, SIBASS allows intersections to switch roles every 5 minutes.

Assigning roles to the intersection state space is doubly challenging. The first challenge is relatively simple; define a complete state space to be used for role assignment. This is necessary to ensure that for any given set of conditions, a role is specifically assigned to that movement. The second design concern relates to role stability, the method of transitioning between roles needs to not introduce instability. SIBASS addresses this issue by making transitions relatively difficult. Thresholds are set such that the intersection needs to effectively overshoot a threshold in order to make the transition. This forces SIBASS to experience more than just a single abnormal interval before changing optimization patterns.

As an example, once queues approach 50% of the distance to the end of the turn bay(s) (either through or turning queues), the Heavy Spinner is the desired role for the intersection. In the example, if the Heavy Spinner role were to reduce queuing and saturation while the Spinner role was insufficient to control queuing and saturation under the given traffic conditions, then every update period the roles would reverse if a simple, single saturation threshold value were used to decide which role to use.

While this behavior might not necessarily be too disruptive if the roles are not allowed to switch too quickly, it is still undesirable. To address this operational concern, role switching thresholds are asymmetrical. For example, if the desired saturation threshold to switch from Spinner to Heavy Spinner is movement saturation above 50%, then the switching threshold to go from Spinner to Heavy Spinner might be 60% and the threshold to shift down from Heavy Spinner to Spinner would be saturation below 40%. This asymmetry is designed to prevent jittering between roles by making sure conditions are clearly beyond the balance point between roles. This behavior also prevents ties, as a role switch is either clearly warranted by meeting or exceeding the asymmetrical threshold or change is not warranted.

After role selection has been completed, SIBASS can start optimizing intersection performance. In this process SIBASS selects the set of non-conflicting movements at the intersection based on minimizing the total of the movement objective functions. The three basic performance measures used by the objective functions are number of stops, sum of vehicle delay (total number of vehicles queued added each time step) and the length of the queue in feet.

The objective function sums the number of vehicles projected to stop in the future multiplied by the value assigned to a stop, plus the accumulated delay of vehicles waiting on those movements times the value of time plus a cost for queuing multiplied by the length of the queue as seen in Equation 7-4. The objective function values for each role are detailed in Table 7-2. The objective function itself is designed to be calculated in monetary units. In this case (projected) stops are worth \$0.25 and time is worth \$18/hour or \$0.005/second. The cost associated with queue length is an arbitrary value developed during SIBASS testing and set to $0.01/foot of the queue.

$$f(x) = v_{stops} * n_{stops} + v_{delay} * \sum d_i + v_{queue} * L_{queue}$$

(7-4)

Table 7-2: Role Objective Function Values

	Main Street			Cross Street		
Role	Stops	Sum Delay	Queue Length	Stops	Sum Delay	Queue Length
Spinner	0.25	0.005	0	0.25	0.005	0
Heavy Spinner	0.25	0.005	0.01	0.25	0.005	0.01
Coordinator	0.25y	0.005y	0.01y	0.25	0.005	0.01
Corridor	0.25y	0.005y	0.01y	0.25	0.005	0.01
Congested	0/0.25	0/0.005	0/0.01	0.25	0.005	0.01
Meter	0/0.25	0/0.005	0/0.01	0.25	0.005	0.01

Note: $y=\sin(\theta t+t_0)+y_0$

7.5 QACD Model Integration

SIBASS is designed to use the QACD model to collect MOE data such as the intersection saturation level, link queuing, arrival rates, etc. The QACD model is not perfect; however, it is a distinct improvement on having only direct sensor data. The QACD model allows SIBASS to estimate important factors, such as queue length, that many traditional systems cannot assess.

Even many adaptive systems, such as SCATS and ACS Lite, use very limited data to operate and optimize. SCATS, for example, bases its optimizations and operations on the degree of saturation. The degree of saturation is calculated based on the gaps between vehicles detected at stop bar loop detectors. The degree of saturation is used by SCATS to determine how heavily traveled each detector and movement is. The degree of saturation also shows a marked decrease when saturated flow due to queue discharge ends, allowing SCATS to identify the point when green time is no longer being spent as efficiently as it could be.

With input from the QACD model, the SIBASS system can be more proactive than systems like SCATS, because it can predict when a queue will discharge prior to observing the event. This allows for better green time allocation because SIBASS can terminate discharged movements more quickly because it does not need to wait to react to changes in observed data.

7.6 VISSIM Models

In order to judge the effectiveness of SIBASS, a series of simulation experiments were conducted. These simulation experiments were conducted using VISSIM 5.40 software to construct models. Figure 7-8 shows the basic corridor simulation used for SIBASS development. This model is designed for basic testing and therefore has limited variables. Specifically, each intersection is identical with separated through, right turn and left turn movements. Intersection spacing and turn bay lengths are also identical.

The corridor model was tested under three different varying volume conditions. Each scenario begins with all side streets having 600 veh./hour arrival rates with 1500 veh./hour for westbound and 900 veh./hour for eastbound traffic. Left and right turn rates are 10% for all intersection approaches at all times. In the first scenario eastbound traffic drops to 600 veh./hour at 15 minutes into the scenario and stays there for 15 minutes before returning to 900 veh./hour for a further 15 minutes. In the second scenario side street traffic increases to 1200 veh./hour at the fourth intersection for 15 minutes. The third scenario increases eastbound traffic from 900 veh./hour to 1500 veh./hour for fifteen minutes.

The inspiration for these scenarios comes from experience at the City of Bellevue. The traffic conditions on NE 8th Street in the morning are highly directional with high volumes coming from I-405 traveling westbound from the 112th Avenue NE intersection through the central business district to the Bellevue Way intersection. Platoons from I-405 quickly disperse onto the side streets as commuters arrive at their destinations. In the space of five intersections, with SCATS providing progression, the platoons are almost completely dispersed before reaching the Bellevue Way intersection. At different times of day north and south traffic on Bellevue Way and 112th Avenue can change the dynamics of the corridor by becoming the dominant movements. At other times of day east or west bound traffic can increase or decrease markedly. These conditions typically occurred on the beginning or end of rush hour or for short periods during lunch time. Observations of SCATS operation of the corridor indicated that additional performance gains could be made under these conditions.

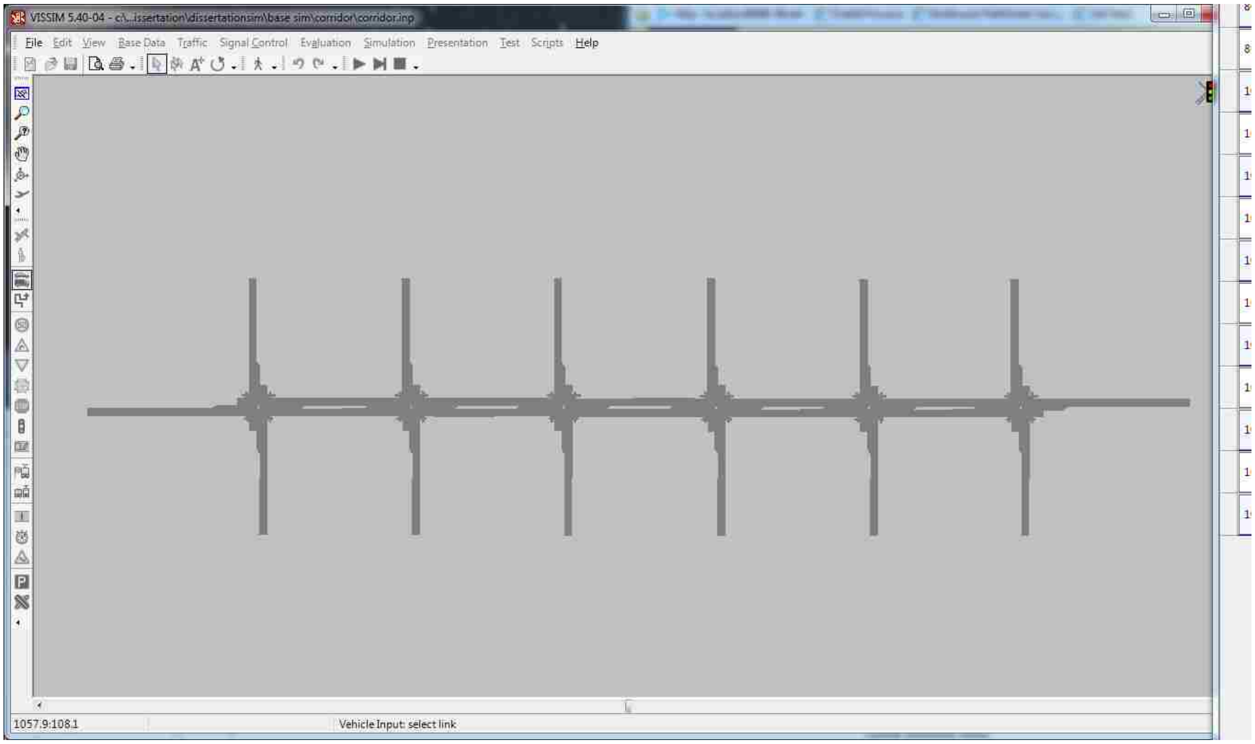


Figure 7-8: Basic Corridor Simulation Model

7.7 Contribution

SIBASS is designed to address shortcomings identified in other systems. The primary concerns being detector failure, communications failure, congestion, coordination and variable demand. SIBASS addresses each of these concerns. SIBASS uses an underlying traffic model and semi-redundant detector layout to address detector failure. Because all decision making is made at the individual intersection level, a communications failure will cause intersections on either side of the failure to act as though they were two distinct groups of SIBASS intersections. Most other systems that lose communications have issues with losing their connection to central control. SCATS, for example, falls back on time of day plans stored in the individual controllers. Depending on the system and fall back control, losing and reacquiring communications can throw the affected intersection(s) into transition.

Reacting promptly to changing traffic conditions is another major concern for SIBASS. Because of the reactive nature of most systems they generally are forced to choose between over and under damped response. Figure 7-9 shows how different degrees of damping affect the response of different systems to a 1 unit change. For $\zeta = 0.0$, the undamped response, the oscillation continues indefinitely because there is no process to stop it. For $\zeta = 0.5$, the underdamped response, the system overshoots and then corrects. The overdamped response, $\zeta = 1.5$, takes excess time to reach equilibrium. The critically damped response, $\zeta = 1.0$, reaches equilibrium as quickly as possible without overshooting. SIBASS is designed to react quickly to changes in demand as well as looking into future arrivals to determine appropriate service parameters. While this cannot guarantee a critically damped response, it does give SIBASS a significantly better chance than systems that react to past measured demand over intervals from 5-15 minutes.

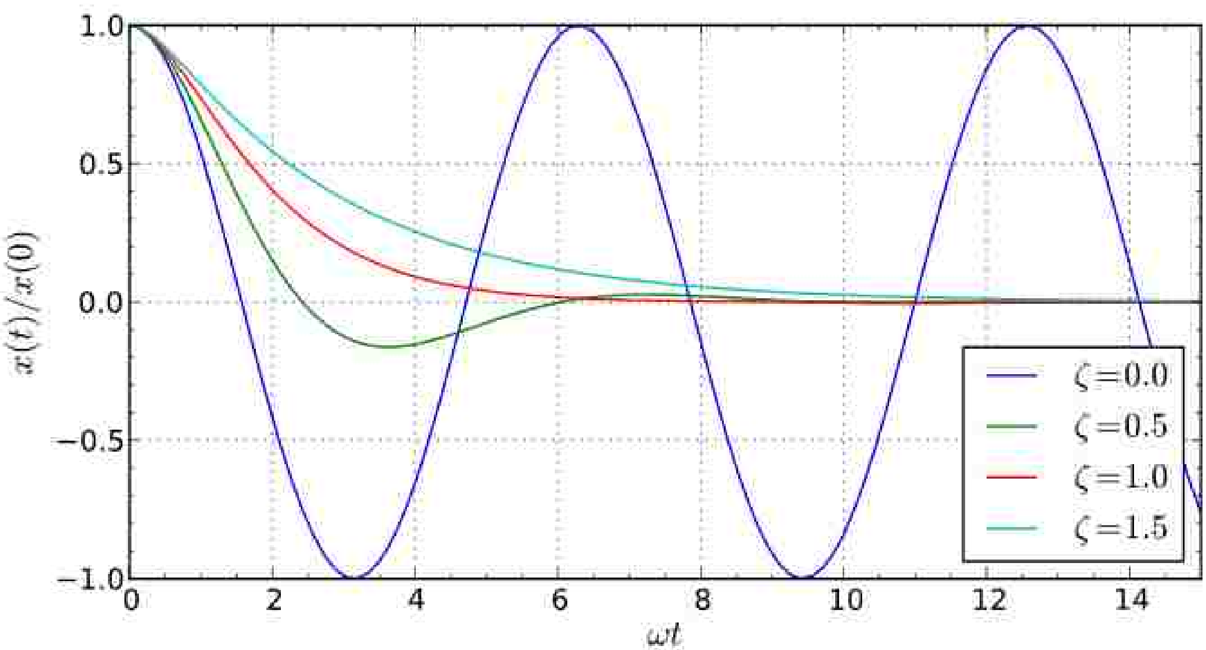


Figure 7-9: Damping Example (Wikimedia, 2014)

SIBASS's ability to adapt to varying traffic conditions is exemplified in the Coordinator and Corridor roles. Between the two roles, SIBASS can react to current conditions and set up coordination on the fly between adjacent intersections. Unlike more traditional systems, SIBASS can change from north-south progression to east-west progression as quickly as the coordinator role can recalculate its coordination function.

7.8 Future Work

The SIBASS system is presented here as a first version system. There are many ways the system can be improved. The most effective is through the inclusion of connected vehicle data. Connected vehicle data will allow the SIBASS system to assign vehicles to specific movements. Additionally, connected vehicle data will help the SIBASS system to calibrate its delay and queuing estimation.

Other improvements to SIBASS include additional signal control considerations. One example is the detection of the yellow trap, where the left turn receives a yellow indication and the opposing through movement receives a green, resulting in the left turn driver thinking the opposing through is also receiving a yellow or red indication and trying to make the turn. This has the potential to result in collisions.

Additional roles may also be developed as needed. A pedestrian focused role is probably required before SIBASS could be considered ready for testing at real intersections. A transit signal priority role is also worth examining for future inclusion in SIBASS. Optimizing based on passenger count is a foreseeable development as well.

Chapter 8: Implementation

The SIBASS system was implemented in C# using Microsoft Visual Studio 2010 and using Microsoft SQL Server 2010 to store the data. The system is implemented using the Component Object Model (COM) interface built into Windows, VISSIM 5.4 and C#. The COM model allows software programmers to expose the functionality of their software to other users through the COM interface. A COM interface is an externally facing interface from a program that is registered with the Windows operating system, and accessible through Visual Studio, allowing users to call COM objects in their own programs.

In this case, VISSIM 5.4 exposes a majority of its modeling, object and simulation functions through a COM interface. Figure 8-1 shows a VISSIM COM object, “Simulation”, initialized under the name “sim” in line 31. Also in Figure 8-1, the random seed value for the simulation is assigned in line 37. Lines 40-43 show the evaluation functions being initialized with specific settings set in lines 45-46 and 48-49. The VISSIM COM interface allows external programs to access signal control functions such as light state (e.g. red, yellow, green) and detector status. From there the C# program can evaluate detector status and signal state to determine what outputs to send to VISSIM when advancing the simulation to the next time step.

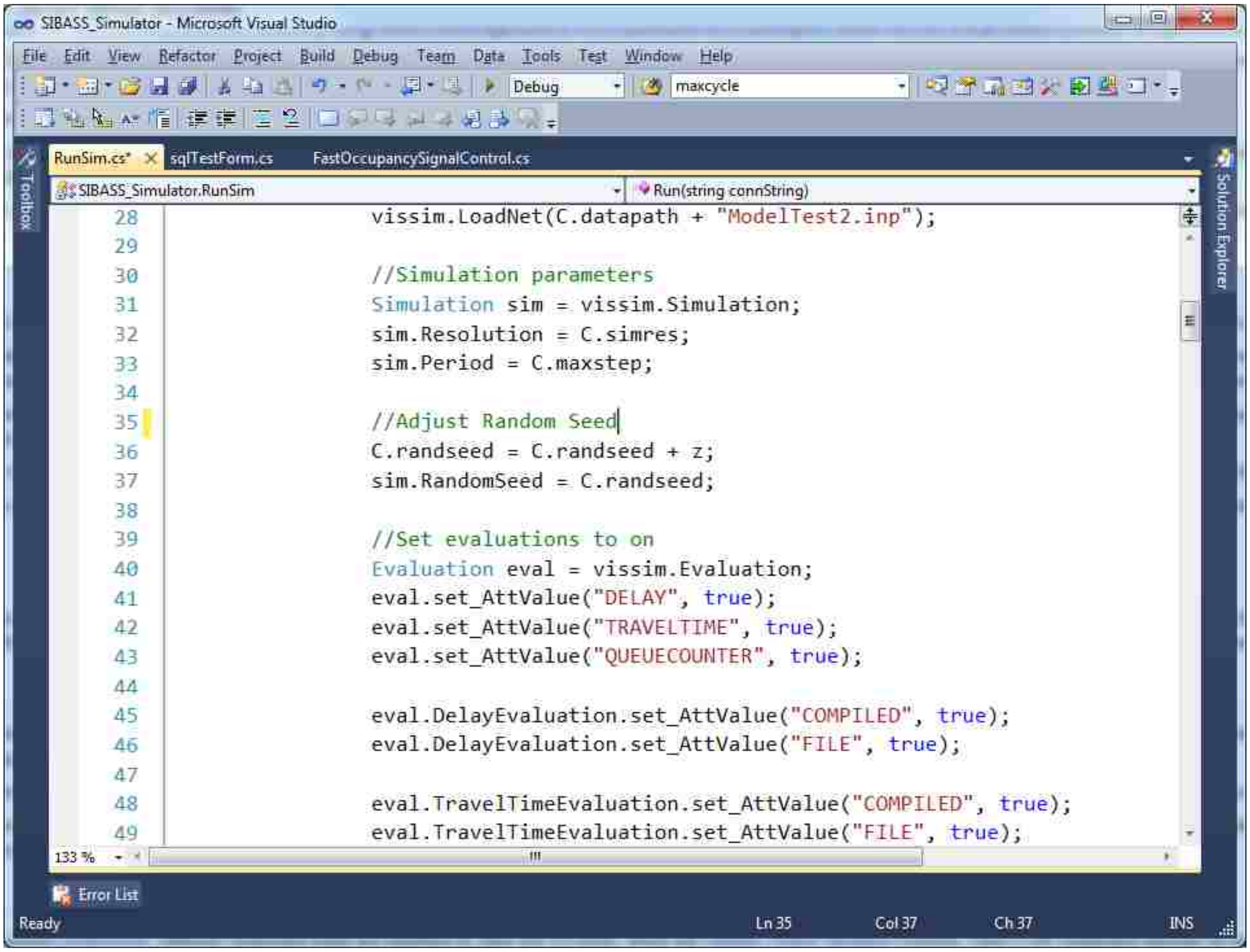


Figure 8-1: Example Code Implementing VISSIM COM Interface

VISSIM is capable of generating different sizes of time steps during simulation. While the simulation may run at 5 or 10 simulation steps per simulation second, the signal control system only updates once per simulation second. As implemented, SIBASS reads the VISSIM detector and signal states for each intersection once per simulation second (to limit computational load) and implements the previously calculated signal control decisions. After reading the data, the C# code computes desired performance measures and relevant signal control data such as presence detection and gapouts for use in the calculation of the next signal state. The third step is to upload current performance measures and system states to the SQL Server database. The fourth step is for the C# code to determine the desired parameters for the next time step. Fifth, the C# code determines the signal control parameters to be implemented next time step. Sixth, the desired parameters are sent to VISSIM across the COM interface. The last step is for the C# code to tell VISSIM to run one simulation time step. For intervals that don't coincide with full second simulation steps, only the last step is executed.

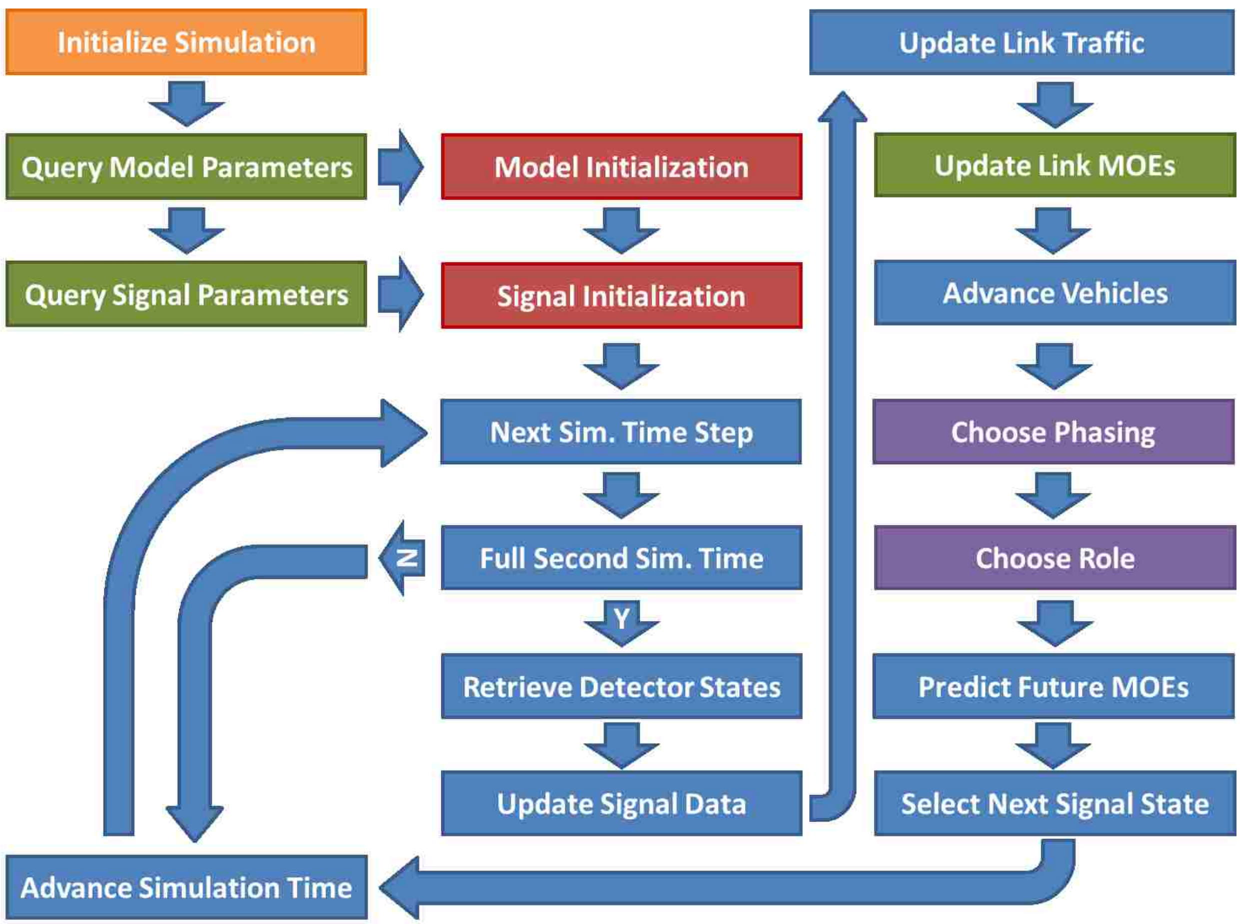


Figure 8-2: Implementation Flowchart

Figure 8-2 shows how the C# code interacts with the VISSIM simulation and SQL databases. The process begins with initializing the simulation and C# COM interface, shown in orange. During initialization the SQL databases are queried for model and signal parameters, shown in green. The C# model objects, the intersection, signal, link and input objects described by the QACD model in Chapter 3 are initialized with the queried data, shown in red. At this point the simulation is actually run in a C# while loop. The while loop begins with a check to see if the current simulation time is an integer value. If it is not, the C# code skips to the advance simulation time step and goes through the next iteration of the loop.

If the current time step is an integer value, the C# code queries each of the VISSIM simulation loop detectors in turn to determine whether they have been occupied in the last second by requesting the “HEADWAY” property from VISSIM. When detectors have been occupied in the last second, they are recorded as sending a presence input for signal control purposes. The headway time also allows the C# code to check for gap outs with the same data request, reducing the number of queries that must be made across the COM interface, which is computationally expensive. Note that the detector data is read for the last simulation time step and does not register changes implemented during the current time step calculations implemented in the C# code until the next time step is run.

After detector states have been read, the C# code sends signal control commands to the VISSIM model. These commands are based on predicted phase selections calculated at the end of the last interval. The C# code will implement the recommended signal control calculated by the current signal role. For the Congested role, gapouts and saturation flow are part of the optimization process and those factors need to be detected. Likewise, the discharge of downstream intersections is important to the Meter role. Link traffic parameters, such as volumes, and MOEs such as delay, queuing and saturation, are updated next. After the parameters have been updated in the C# code, they are sent to the SQL database, shown in green, if the current time interval is a multiple of one minute.

After the link traffic parameters have been updated and MOEs sent to the SQL database, the vehicle objects associated with the link are advanced. New vehicles generated by link inputs or traversing upstream segments are randomly assigned to through, right or left turns based on the observed turn rates for that link. Vehicles that reach the end of a link are transferred to the appropriate link based on their origin link and movement made. This data is predicted, and not considered final until the departure is verified by stop bar detection and the movement confirmed by exit detection in subsequent time intervals. Note that missing detectors can be worked around based on the redundancy of detection and conservation of vehicles. A vehicle detected at a downstream detector must have come from an upstream source. So long as only one detector fails for each group of movements, the missing detector's volume can be imputed.

Every five minutes the SIBASS C# code evaluates whether to change phasing and optimization role, as shown in purple. These steps are skipped when the current time interval is not a multiple of five minutes. SIBASS control chooses a new phasing pattern based on observed volumes and phasing restrictions assigned to the intersection. These calculations, described previously in Chapter 7, revolve primarily around determining which left turn phases require protected-only phases in addition or exclusion to permitted left turn phasing. Role choices are based primarily on the observed link MOEs.

Once a role has been chosen, SIBASS calculates the predicted number of stops, sum of delay and queue length that will be observed over the next 10 seconds as well as an appropriate green time allocation for a given phase. When the current phase is due to be terminated, the next set of phases is chosen to minimize the stops, delay and queue length seen at the intersection. That set of phases is then readied for implementation during the next time step.

Chapter 9: Evaluation

The introduction of a new traffic signal control system requires extensive testing at a number of different levels, the beginning of which is an investigation via simulation as presented here. This first step has been conducted on a VISSIM 5.40 simulation model of a six intersection corridor. The size and configuration of the corridor has been designed to require operational compromises. Specifically, the corridor is long enough that true bi-directional progression along the main corridor is not practicable. Using offsets only to create progression in the eastbound direction results in serious impediment of westbound traffic, specifically eastbound performance is bought at the expense of westbound stops and delay. Using a pattern of lead and lagging left turns in addition to offsets results in eastbound progression across all six intersections with westbound progression across three intersections being an achievable level of progression. This corridor represents a more challenging scenario than is typically used for traffic signal control evaluations of new systems due to the progression factor.

Three test scenarios were created to mimic different conceptual problems encountered in practice. The default traffic condition on the corridor is 1500 vehicles/hour eastbound and 900 vehicles/hour westbound with 600 vehicles/hour on each northbound and southbound approach. Each test follows the same pattern: default conditions for 15 minutes followed by test conditions for 15 minutes and then resuming default conditions for 15 minutes before terminating the test. This testing pattern illustrates the ability of each system to react to new conditions and then resume normal operations. Both reaction and resumption of normalcy are important because it is desirable for a system to react to new conditions quickly, but not at the expense of performance during prevailing conditions.

Scenario 1 is the simplest with a drop of opposing through traffic changing the east-west traffic balance. Scenario 2 doubles the cross street traffic at the fourth intersection. Scenario 3 brings westbound corridor traffic up to eastbound levels for a short period. Note that all approaches have 80% through traffic with 10% turns each direction.

9.1 Performance Measurement

Figure 9-1 shows the various locations chosen for comparison in the following sections. The top image in Figure 9-1 shows intersection number 4 highlighted. The performance of each approach of intersection number 4 is shown in the following sections, broken out by approach and phase. The middle picture in Figure 9-1 shows the segments comprising the corridor for performance comparison. The bottom image highlights each segment in the simulation where performance measures were gathered. Performance for each through/right and left turn lane was recorded and totaled for comparison.

A number of systems were tested for comparison to SIBASS. Conventional systems such as fixed time and actuated were tested. The adaptive strategies used in STATICS including slow occupancy, fast occupancy and delay optimization, were also tested. These strategies are described in Chapter 3. The conventional and slow occupancy systems were found to have second tier performance. This is based on the testing case of 15 minutes combined with an assumed plan change interval of 15 minutes. The conventional systems and slow occupancy couldn't react to the change in traffic conditions effectively. When they were allowed to change plans (to optimized plans for the testing conditions) in 15 minutes, they would change plans just in time to return to default conditions. When they weren't allowed to change plans, the conventional systems didn't react to the change in traffic conditions and performed poorly as expected. The slow occupancy system only changes phase splits by 3 seconds each 5 to 15 minutes, causing the slow occupancy system to react too slowly to be effective in adjusting to the test conditions and slow in readjusting back to the default conditions. It is important to note that this test corridor configuration is intended to highlight deficiencies in current systems, so it is unsurprising that several systems performed badly.

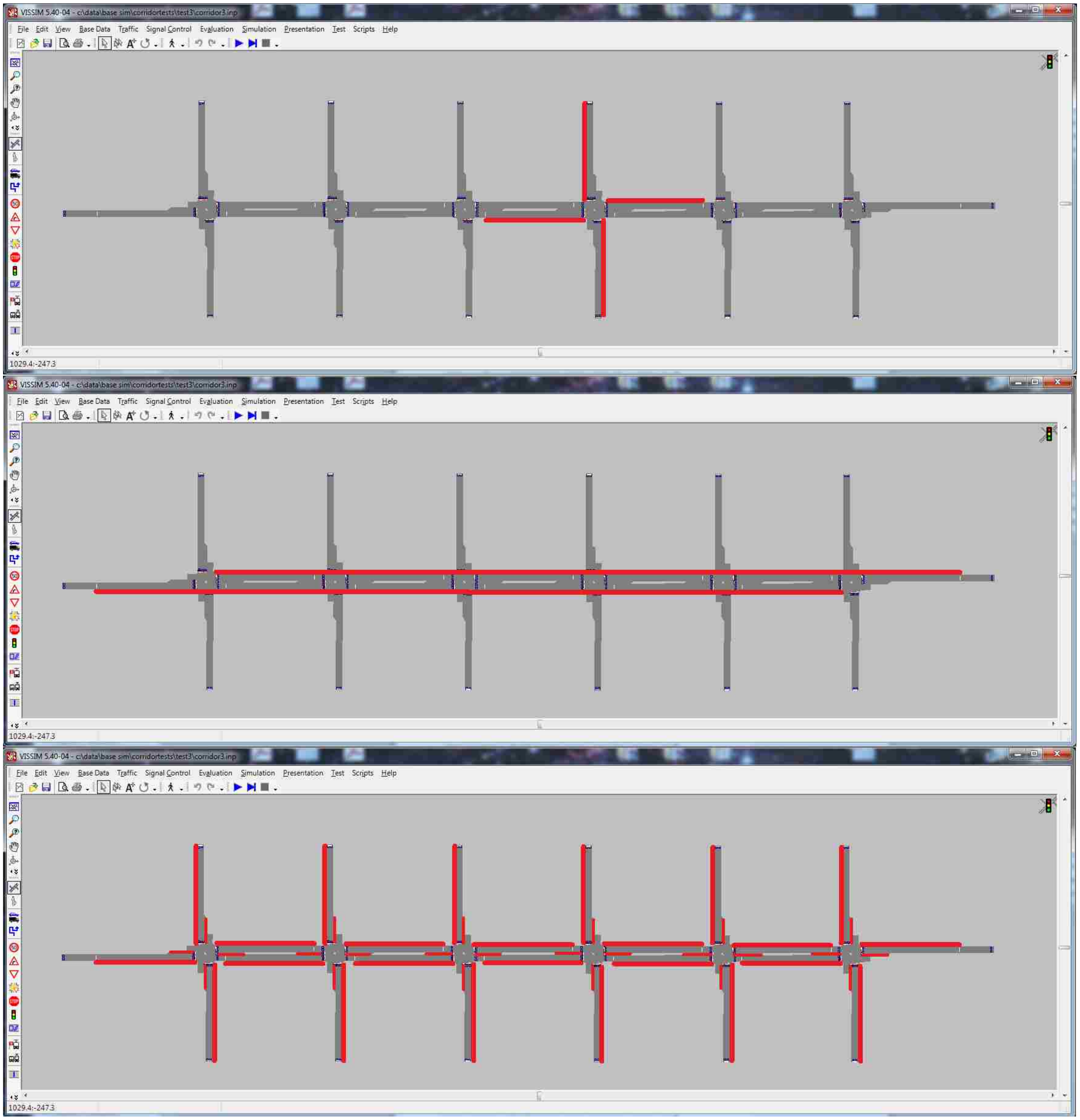


Figure 9-1: Performance Measurement Groupings

The fast occupancy and delay optimization systems performed better. The fast occupancy system came in second in performance to delay optimization for comparison to SIBASS. The fast occupancy system performance was limited by the logic for aligning the intersections. With the first (leftmost) intersection experiencing 1,500 vehicles/hour as an eastbound input, that intersection had a substantially higher cycle under fast occupancy than the other intersections and the logic for linking intersections drove them to higher cycles as well. This would not be too detrimental, except the current limited logic does not adjust offsets as well as it could. Observations of SCATS indicate that the current version of the system has a mechanism for adjusting the offsets that is more effective than the linear one used in the generic fast occupancy strategy. The delay optimization logic turned in the best overall results and will be used for comparison purposes for the remainder of the chapter.

Figure 9-2 shows the steady state volumes each intersection experiences during the default conditions, note that while the first intersection experiences a total volume of 3,400 vehicles/hour with eastbound traffic dominating at over twice the traffic on any other approach, the sixth intersection in contrast experiences just under 3,000 vehicles/hour with nearly equal east and westbound traffic. This set of conditions limits most systems' ability to serve the corridor since required green bands are asymmetrical and the intersections have different directional ratios making green time allocations for green bands difficult.

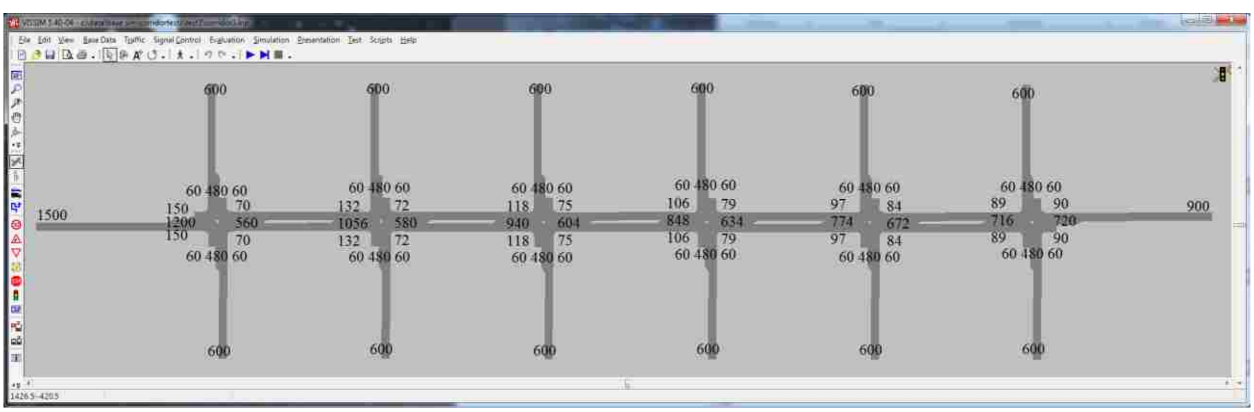


Figure 9-2: Steady State Volumes under Default Conditions

9.2 Corridor Test 1

Test scenario 1 puts 600 vehicles/hour on all side streets and 1500 vehicles/hour eastbound on the corridor. During the first 900 seconds (15 minutes) of the test 900 vehicles/hour are input westbound on the corridor, dropping to 600 vehicles/hour for the middle 900 seconds and rising back to 900 vehicles/hour for the final 900 seconds as seen in Figure 9-3. This test is a simple gap in waves of traffic.

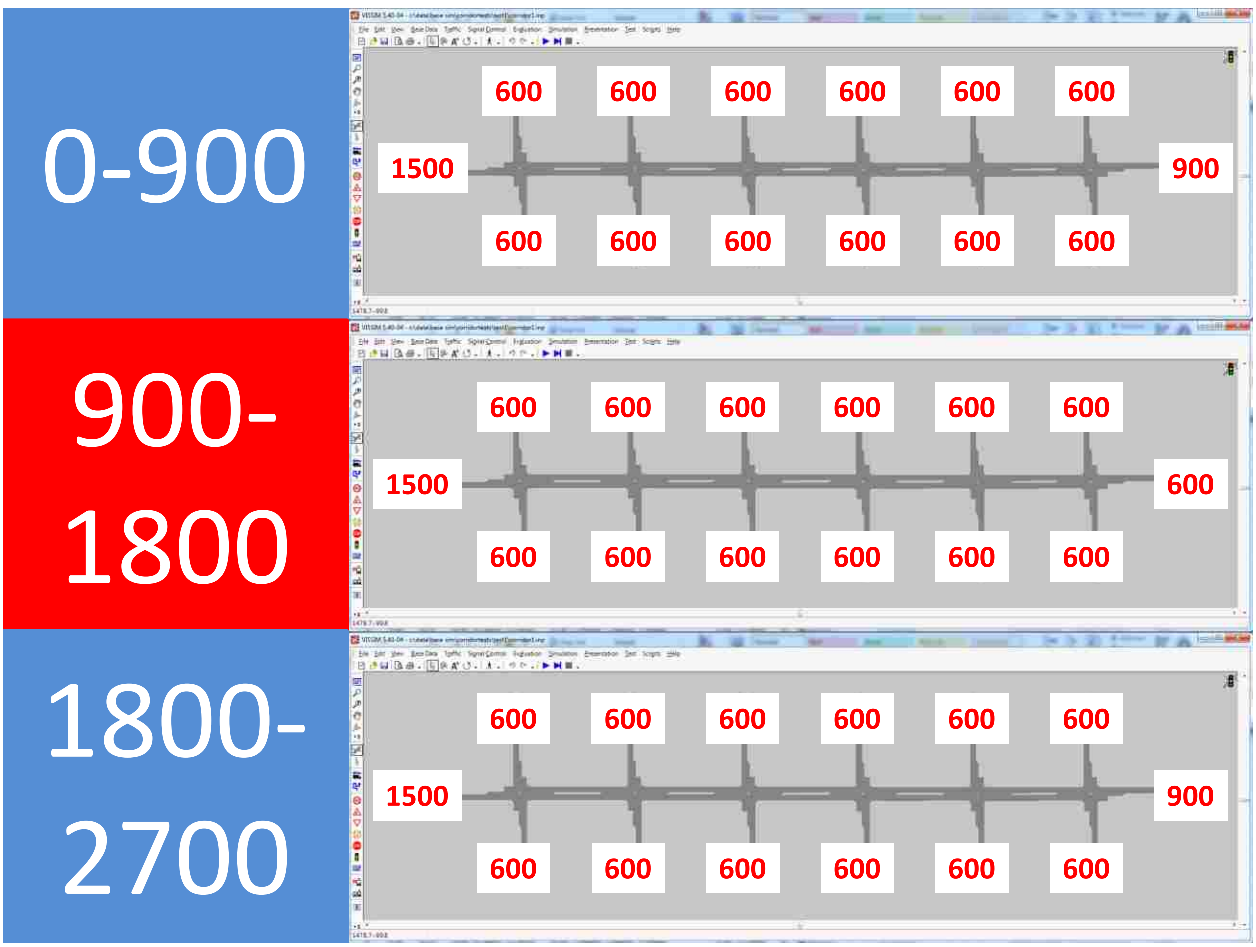


Figure 9-3: Test Scenario 1 Volumes

9.2.1 Delay

Delay is a very common measure of traffic signal system performance measurement. For this analysis there are six charts showing delay as part of Figure 9-4. These six charts show the through and left turn performance for each approach of intersection 4, the corridor segments and the total system delay.

As can be seen in Figure 9-4, the SIBASS system offers a significant improvement in performance over the delay optimization system tested for test 1. The corridor delay difference is particularly striking with SIBASS delivering a significant improvement over the delay optimization results. Closer examination of the results shows that the delay optimization methodology has difficulty creating meaningful progression in the westbound direction, particularly with the low traffic westbound. A quick look at the nature of platoons on this corridor offers a reason why. With only 80% of traffic entering each link proceeding on through movements, the platoons break up quickly. At the first intersection 80% of the input travels through, reducing to 64% at the second intersection and then 51.2% at the third. The fourth intersection only sees 41% of the platoon that began at the first intersection. The fifth intersection sees one third of the initial platoon and the sixth intersection passes one quarter of the original platoon.

This attrition of the platoon limits the delay optimization strategy's effectiveness in general. Note that this problem is not limited to the delay optimization strategy. Every system has some difficulty associated with platoon break up. Platoon break up was also part of what made progression under fast occupancy control fail. SIBASS is able to realize benefits because it uses the QACD model to more accurately react to the size of the platoon as it disintegrates.

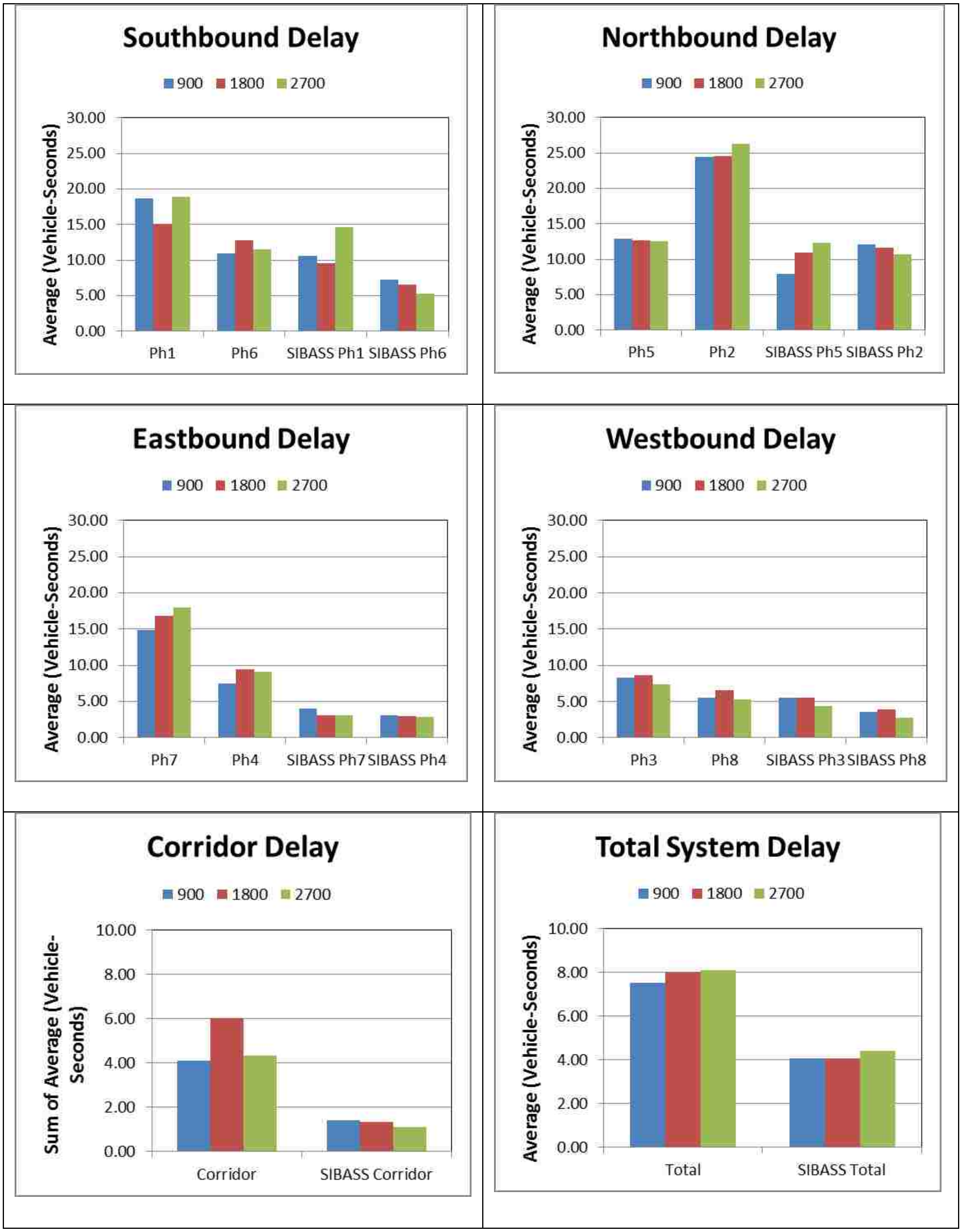


Figure 9-4: Delay by Approach for Corridor Test 1

9.2.2 Stops

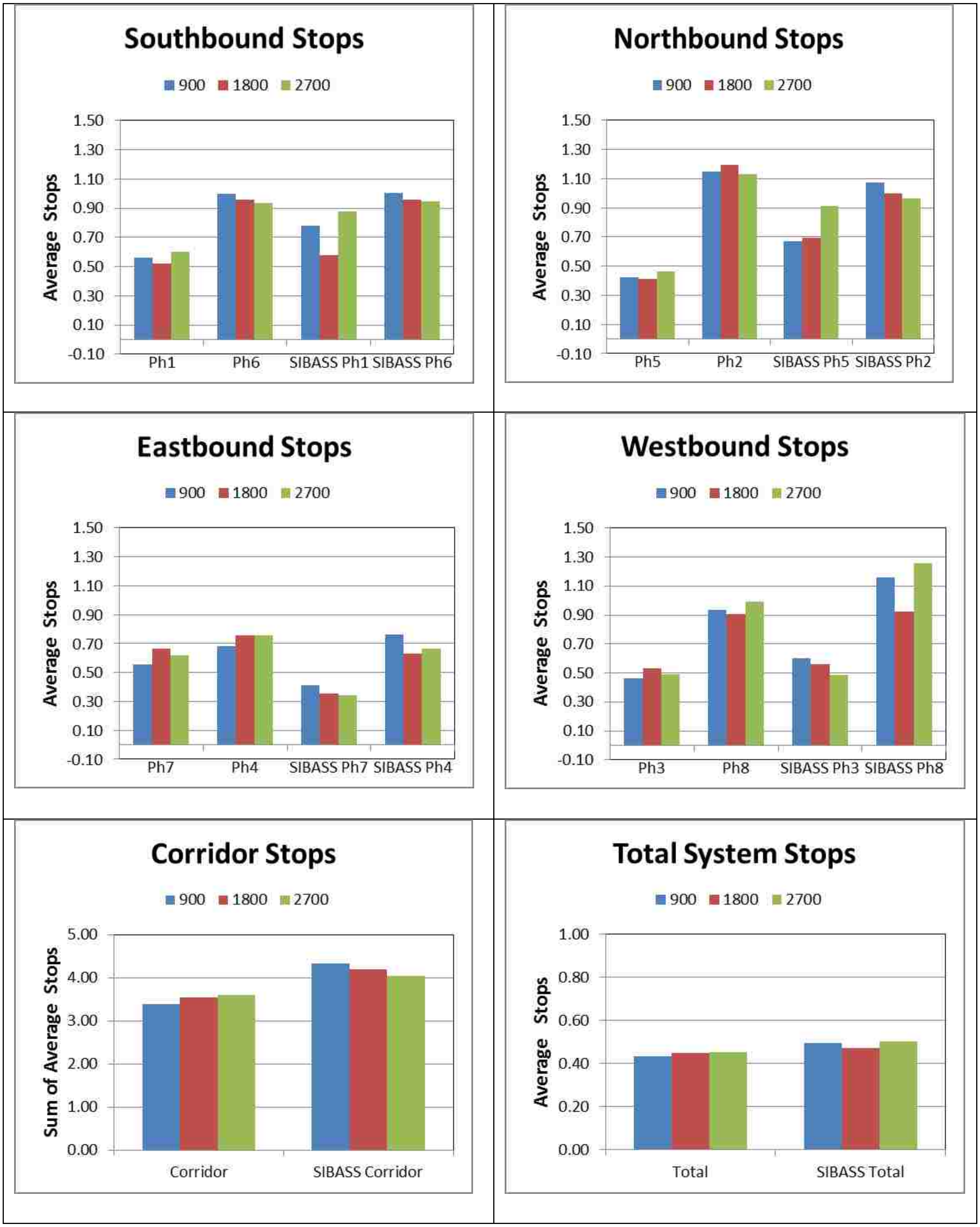


Figure 9-5: Stops by Approach for Corridor Test 1

The number of stops a traffic signal control system inflicts on drivers is an important measure of the user experience. Even if delay and queuing are better for a given system, drivers are likely to be unhappy to be stopped frequently while driving. A comparison of SIBASS and the delay optimization system's average number of stops indicates that SIBASS has comparable performance to the delay optimization system as seen in Figure 9-5. There is effectively no difference between the systems when comparing stops for this test scenario.

9.2.3 Queues

Queuing is an important aspect of system performance and safety. Queues protruding from turn bays place stopped traffic in lanes expected to be flowing, increasing the risk of collision. Similarly, a turn bay occluded by a through lane queue cannot operate effectively and represents an operational limitation. Figure 9-6 shows the queuing observed during test scenario 1.

SIBASS significantly outperforms the delay optimization system in queuing for test 1. Observation indicated this performance differential could largely be attributed to reduced phasing complexity used by SIBASS and the attendant reduced chance of queuing in left turn bays accumulating when platoons arrive after left turn service. Note that the corridor queue is somewhat misleading as it is the sum of average corridor queues (phases 4 and 8) and not the average of average queues as the total system queue is.

Note that when queues extend past an upstream intersection, the full queue is measured past the beginning of the next intersection's queue counter and the portion of that queue from the upstream intersection to the end of the queue is measured again for that intersection's queue. For example, a queue from intersection 1 to 200 feet past intersection 2 would be measured as 600 feet long at intersection 1 and 200 feet long at intersection 2. This is effectively double counting the impact of large queues.

With the delay optimization system's limited ability to produce a green band that would be utilized from end to end along the corridor, the delay optimization system occasionally creates a large queue by stopping platoons early. This happens when the two opposing green bands align to create conditions where the side street cannot be served. In test 1 this occurs at intersection 4 where side streets see noticeable queuing compared to SIBASS operations.

In many ways, this test scenario offers a best case application scenario for SIBASS operations. The corridor, as loaded, is under capacity and can be served with relatively simple phasing on an individual intersection basis. It is the corridor as a whole that needs more elaborate phasing to improve performance and green band generation.

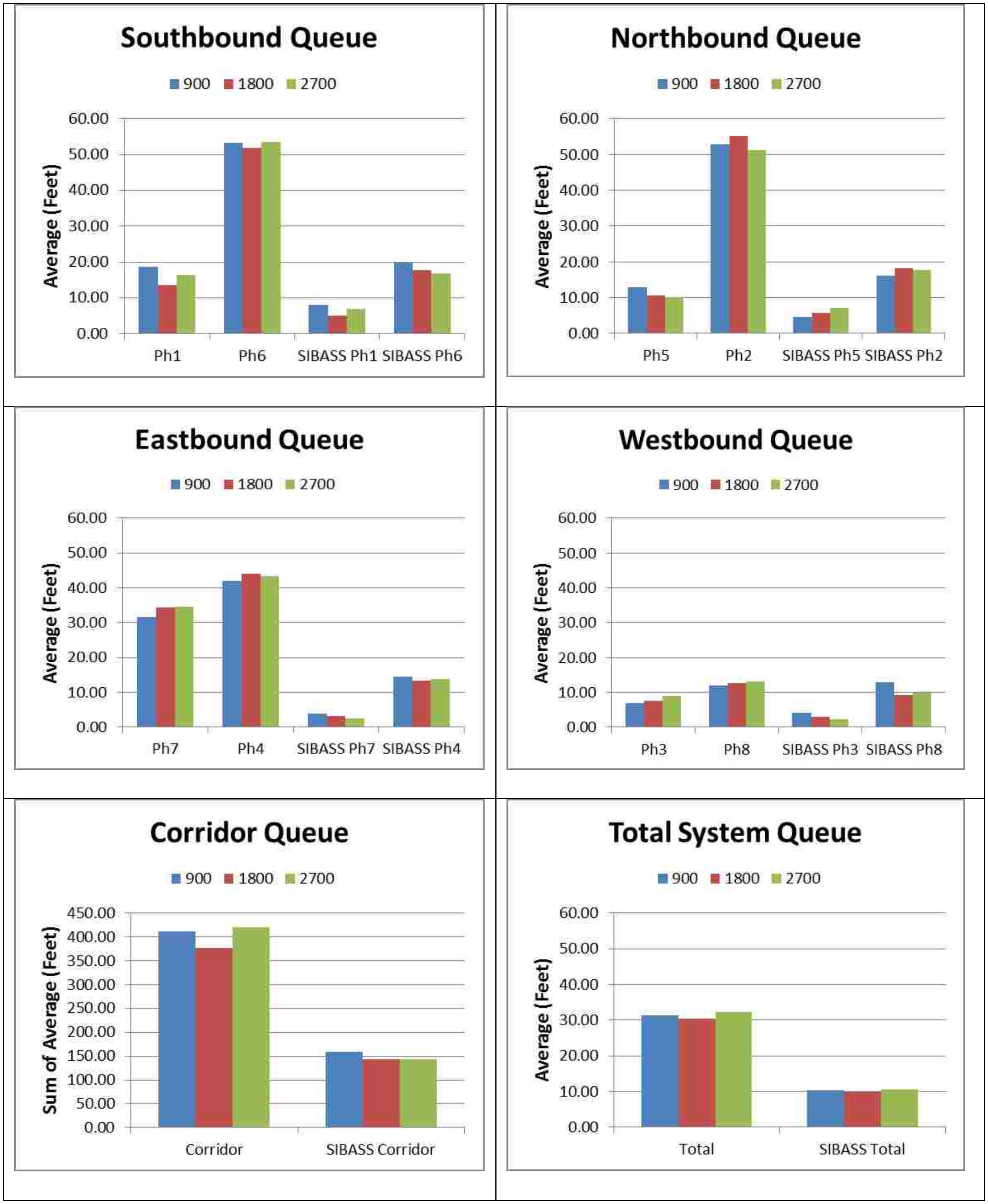


Figure 9-6: Queues by Approach for Corridor Test 1

9.3 Corridor Test 2

Test scenario 2, detailed in Figure 9-7, is intended to represent a situation such as a school dismissal, manufacturing plant shift change, or other temporary high volume discharge. In practical terms, a discharge of this nature offers a challenge to conventional systems. In this scenario the discharge lasts for 15 minutes, long enough to be problematic, but not long enough to justify changing plans for. It may actually be impossible for a conventional system to be set to react to such a short duration, high intensity event, but any variation in time or duration would render the associated plan meaningless.

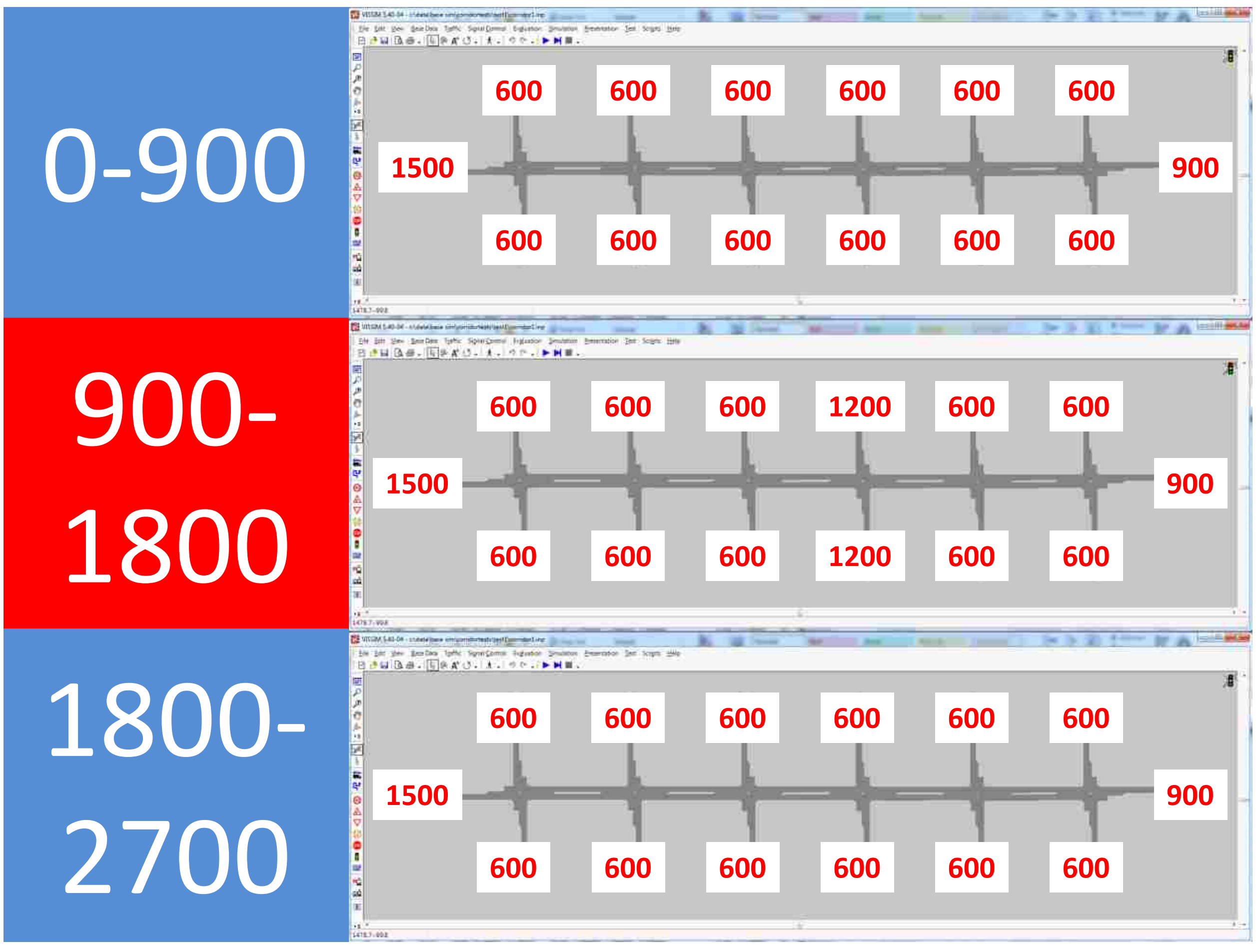


Figure 9-7: Test Scenario 2 Volumes

9.3.1 Delay

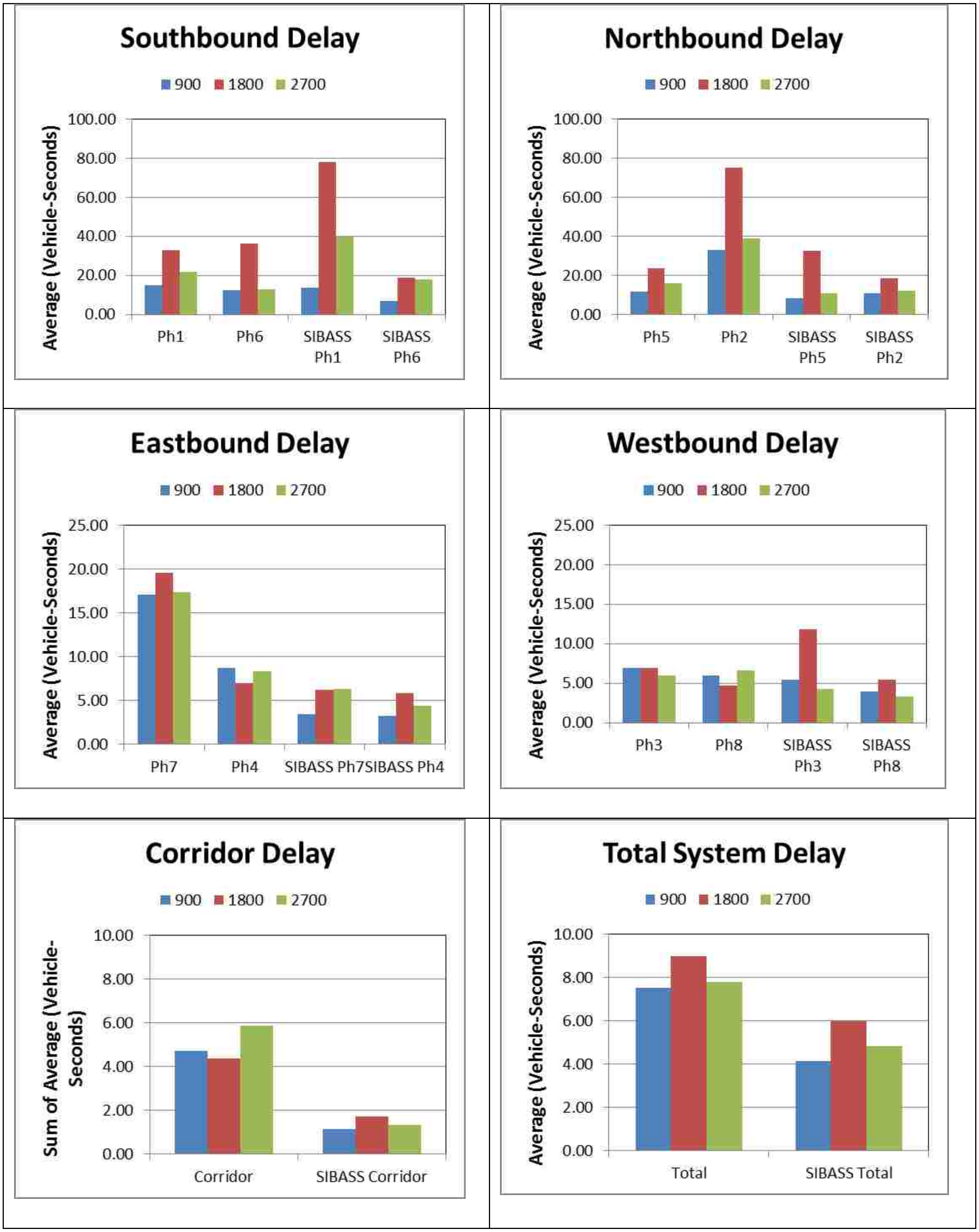


Figure 9-8: Delay by Approach for Corridor Test 2

In general SIBASS performs well in this test. There is one glaring exception. An examination of southbound left turn delay indicates that one or more cycle failures occurred as queues built up from the increased traffic volume across the corridor. This will be discussed in greater detail with relation to queuing as seen in Figure 9-10. Note that the increased north and south bound traffic changes the directional bias from east and westbound to north and southbound. When this happens, intersection 4 becomes the most saturated intersection at about 4,400 vehicles/hour compared to the 3,400 vehicles/hour at intersection 1. SIBASS selects intersection 4 to assume the Coordinator role from intersection 1 at the next 5 minute interval and reevaluates its coordination parameters in reaction to the new conditions at that time.

9.3.2 Stops

Test scenario 2 is not an easy problem to solve. With the increased side street volume eclipsing westbound traffic, some changes need to be made to priority and phasing to serve the new demand. Note that the 1,500 vehicles/hour eastbound from the western end of the corridor are reduced by 20% at each intersection by turns, leaving just over 600 eastbound vehicles/hour and just under 600 westbound vehicles/hour reaching intersection number four from the end of corridor inputs. Adding in the vehicles turning on to the corridor from the side streets there are 1,060 vehicles/hour headed eastbound and just under 800 vehicles/hour heading westbound compared to 1200 vehicles/hour each on north and southbound approaches at intersection 4. In practical terms this means the intersection should orient its service to the cross street rather than the corridor given that there is roughly 25% more traffic north/south compared to east/west.

Figure 9-9 shows the average number of stops observed each minute by approach. One conclusion that may be drawn is that SIBASS has room for improvement with regard to left turn service for high volume movements. There is more to the story, however, that will be discussed with regard to queuing and Figure 9-10. Note that SIBASS increased the number of stops experienced by westbound traffic, while delay actually decreased. Closer inspection indicated that the westbound traffic was receiving the lowest priority and that additional tuning regarding SIBASS phase changes would reduce the stops incurred.

The delay optimization system continued to provide green bands from one end of the corridor to the other, explaining the relatively low delay for east and westbound traffic. Similarly, east and westbound stops are also low for the delay optimization system. The increase in delay and stops for north and southbound are unsurprising when crossing traffic doubles.

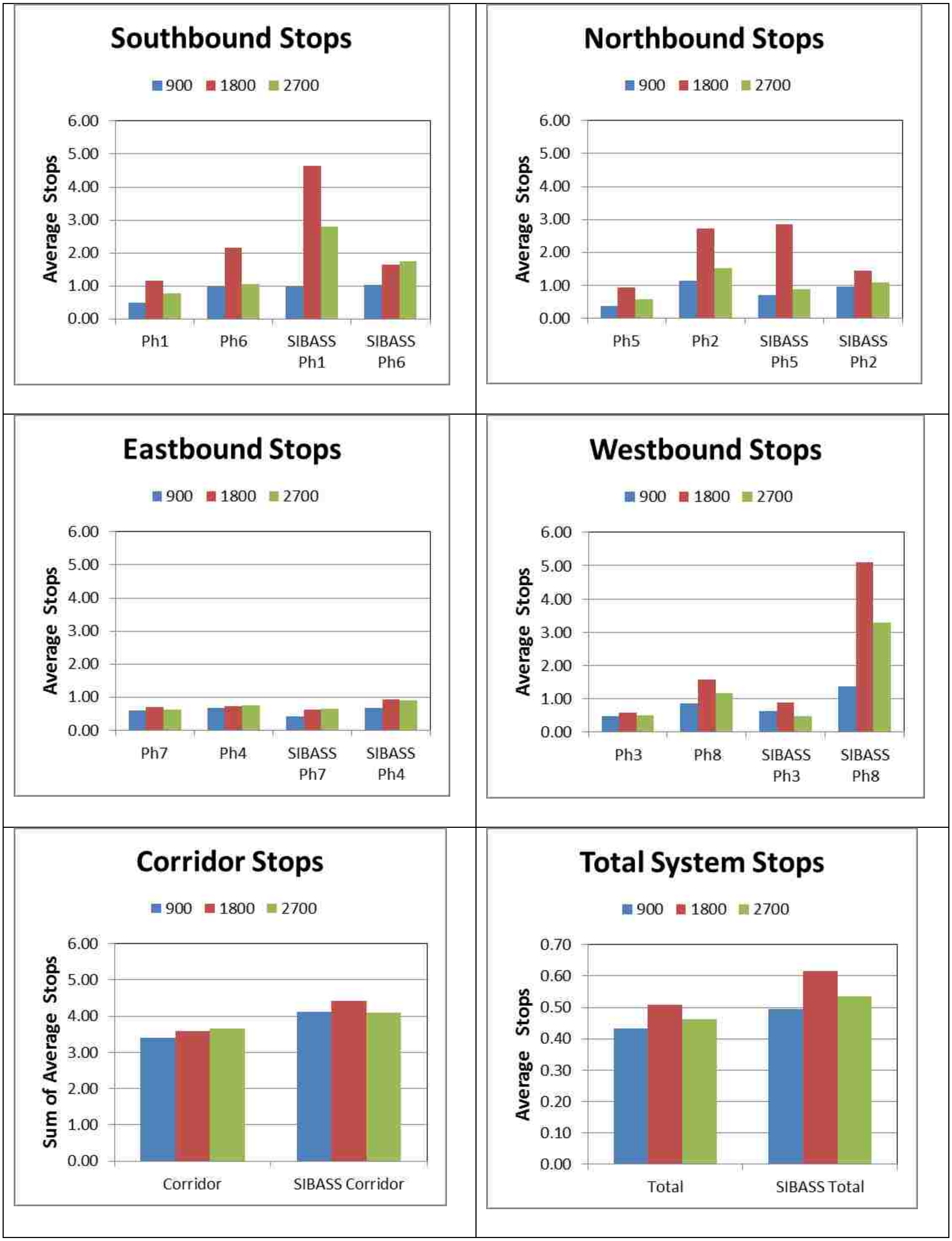


Figure 9-9: Stops by Approach for Corridor Test 2

9.3.3 Queuing

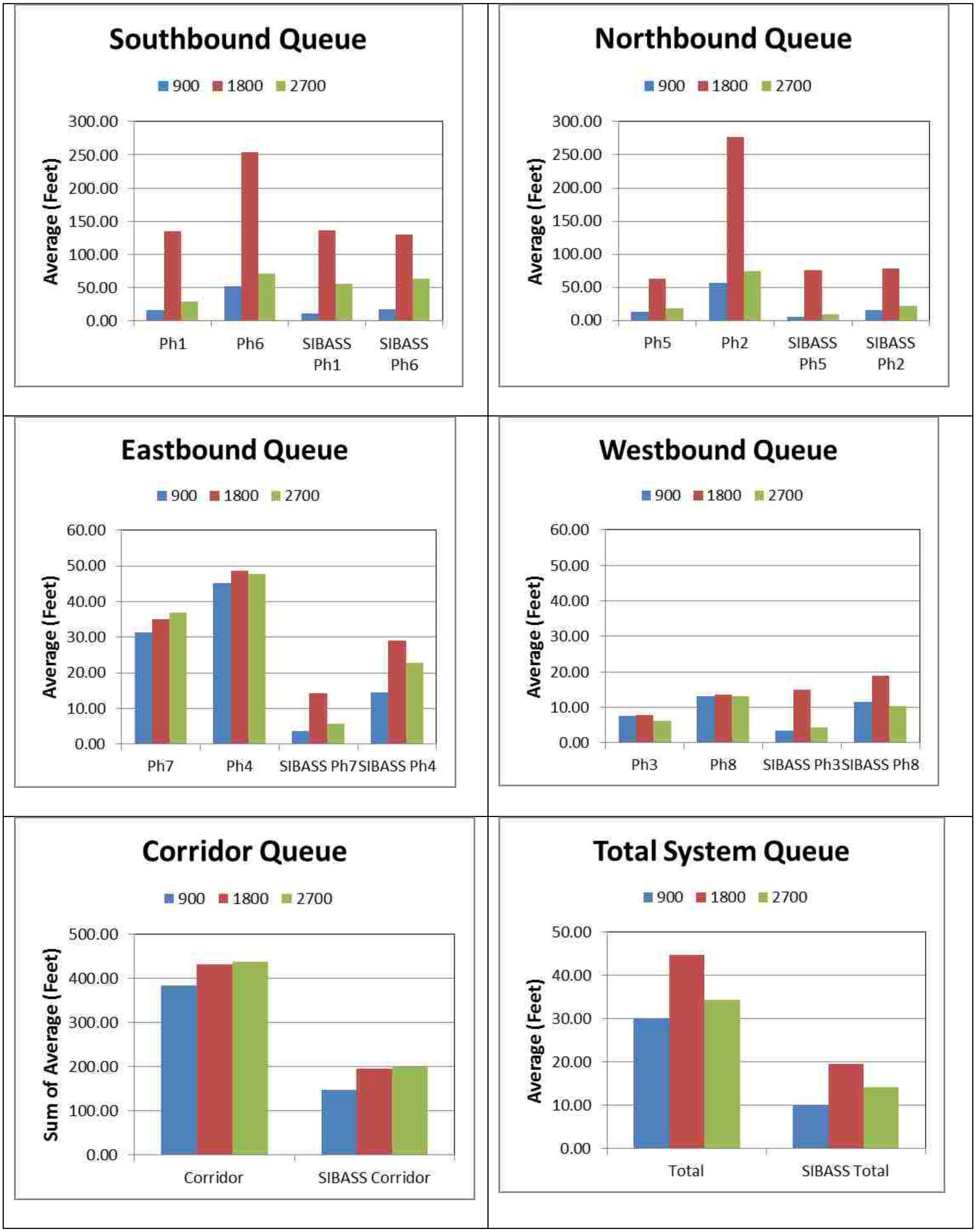


Figure 9-10: Queues by Approach for Corridor Test 2

Figure 9-10 shows the queuing observed on each approach for test scenario 2. The important detail to notice is that the average southbound queuing exceeds 200 feet when the turn bays are 100 feet long. This means that left turn queues are spilling out and affecting the through traffic and that the through queue is also occluding the left turn bay. Observations indicate that the two queues engaged in alternating advancement until a queuing vehicle would stop the other movement from advancing. The net result is that starvation terminates the through and left movements when blocked vehicles cannot make it past the occluding queue. The ironic part of this problem is that the fixed time service plan actually served left turns better by holding on to the service long enough for the queue blockages to sort out during concurrent service.

9.4 Corridor Test 3

Test scenario 3 is a reversal of test scenario 1. This time the eastbound traffic input increases to equal the westbound traffic at 1,500 vehicles/hour. Such behavior may be expected along commercial corridors where intermittent traffic such as seen during lunch time may drive traffic conditions and directions.

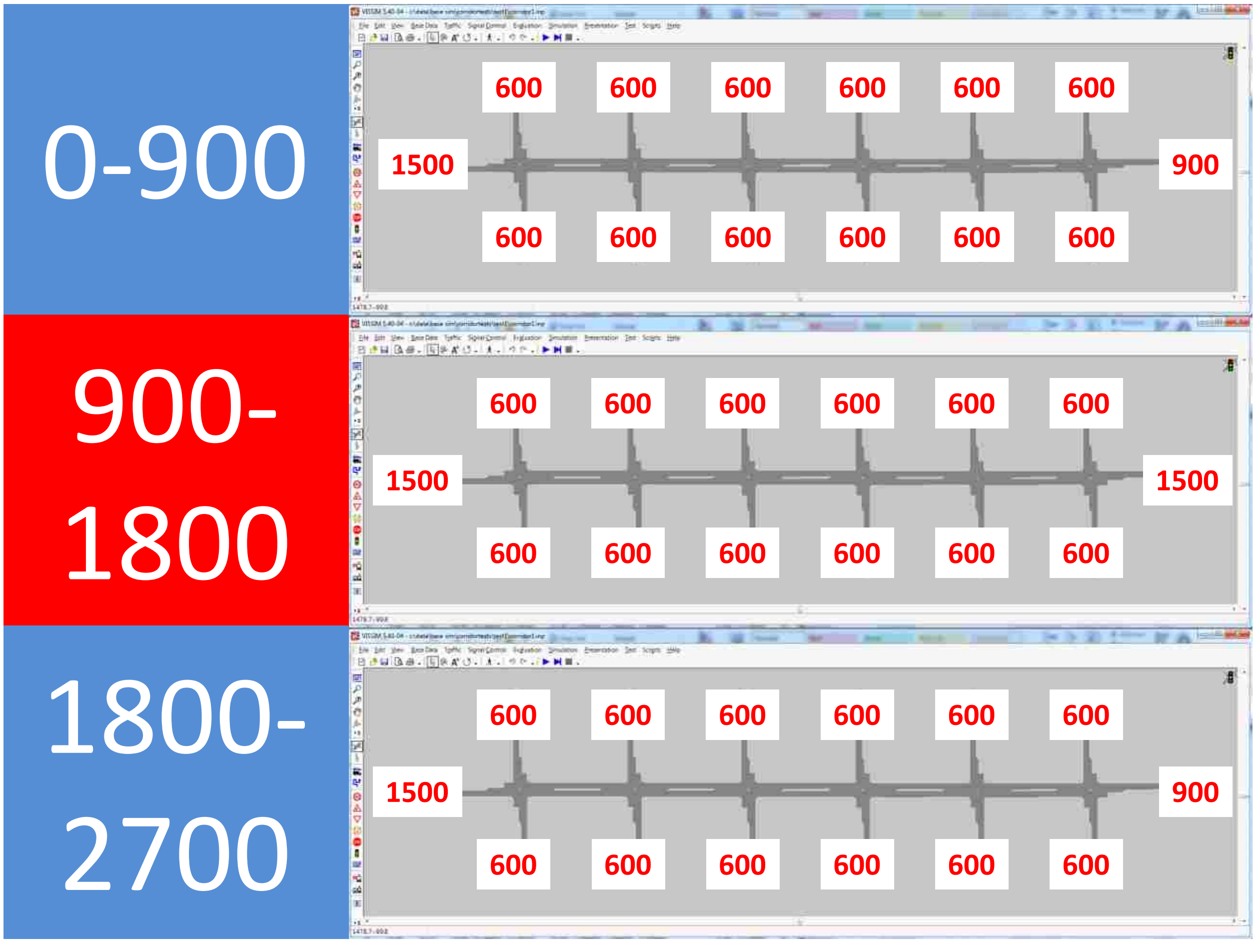


Figure 9-11: Test Scenario 3 Volumes

9.4.1 Delay

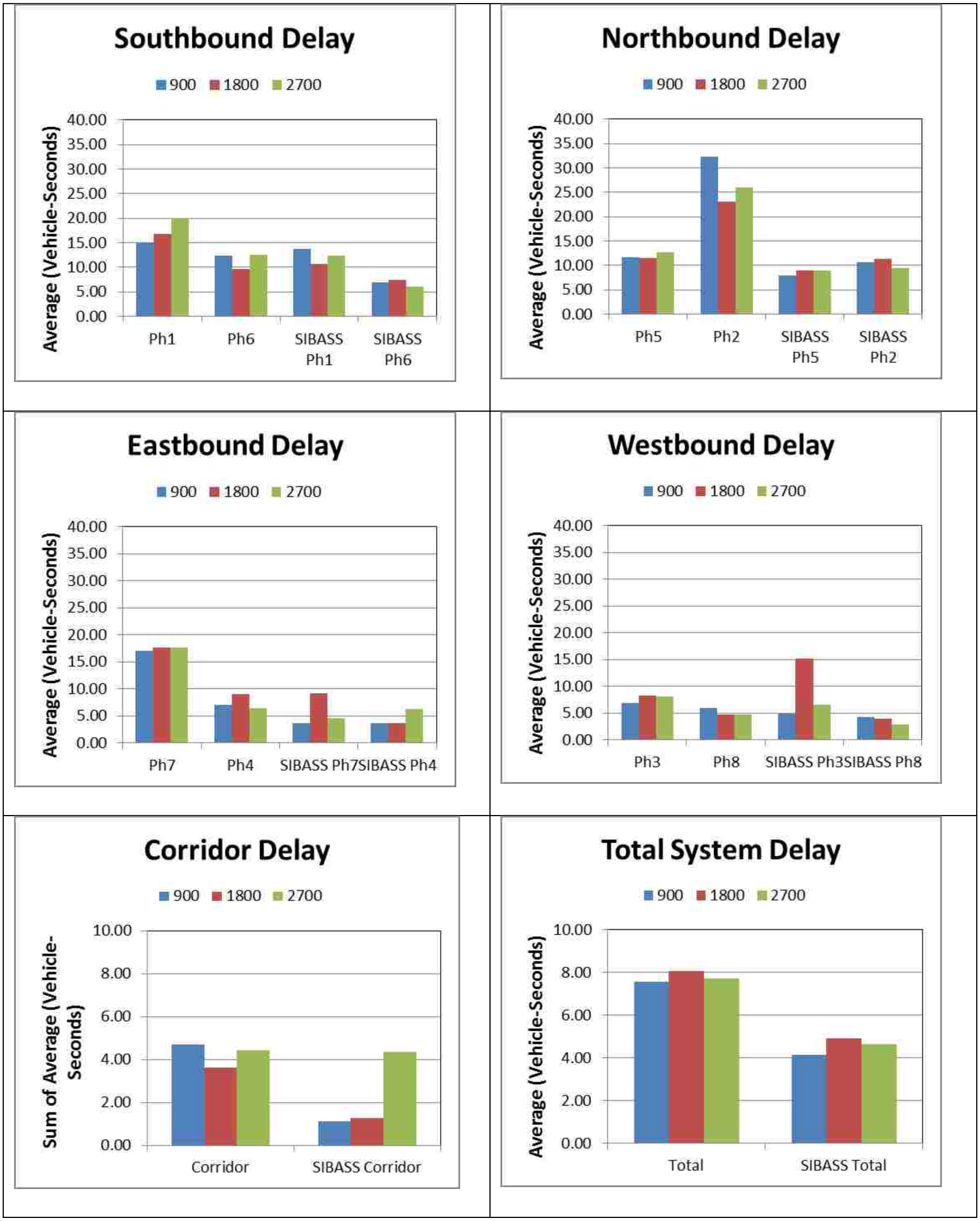


Figure 9-12: Delay by Approach for Corridor Test 3

There are a few noteworthy occurrences in the delay data. First SIBASS generally performed better than the delay optimization system. However, there are a few spikes in delay that need to be explained. The phase 3 and phase 7 delay increases during the increased volume interval corresponds with reduced left turn service in favor of main street service and progression. The corridor delay increase after the testing interval corresponds with a slow return to the default conditions by SIBASS. This slow return occurred because sufficient vehicles were still in the corridor to cause the 5 minute update process to not change roles and phasing until the next interval.

9.4.2 Stops

For this scenario, stops are a relatively meaningless description of performance. Neither system differentiates itself from the other except for outliers. The spikes in delay noted above correspond to spikes in stops as expected.

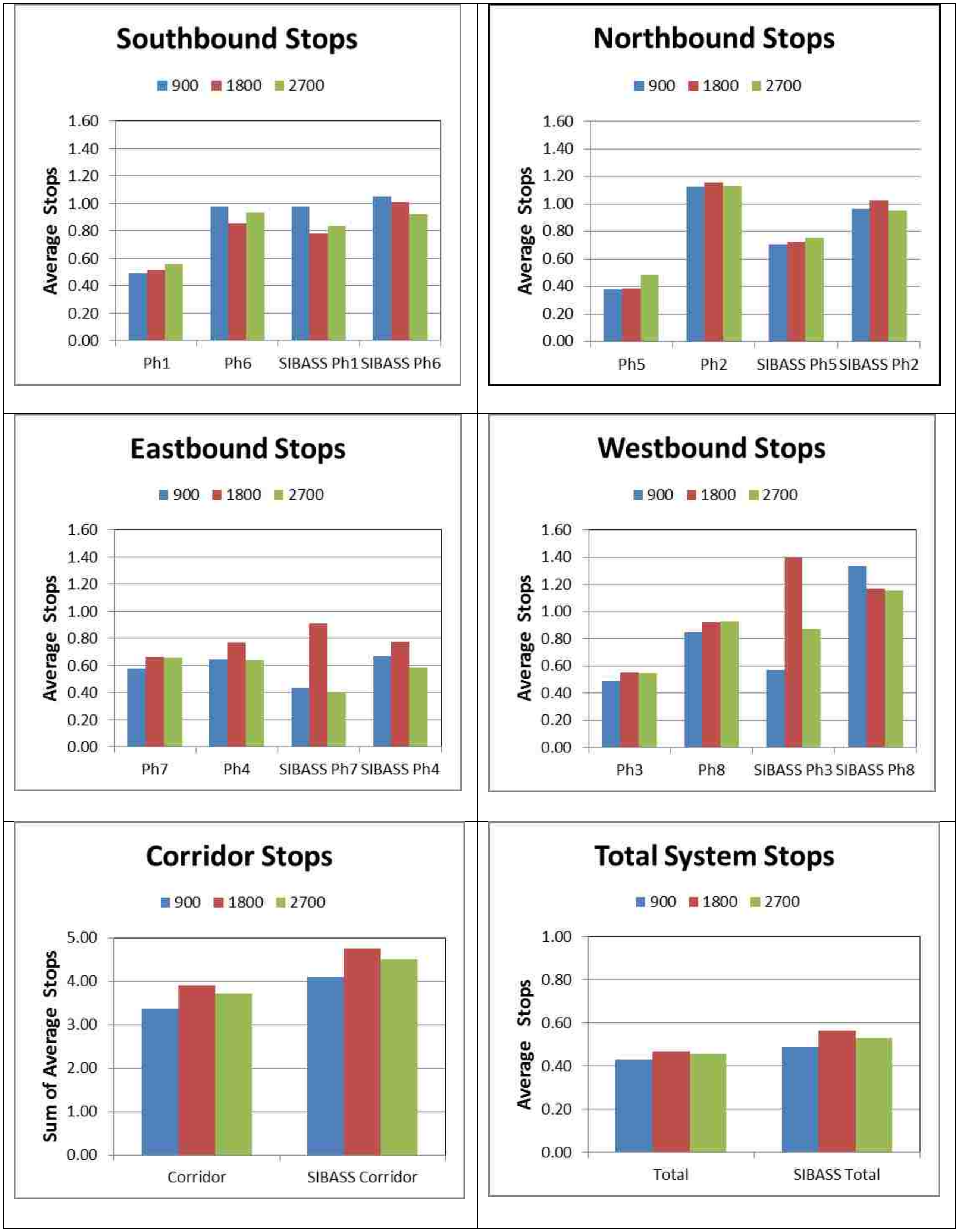


Figure 9-13: Stops by Approach for Corridor Test 3

9.4.3 Queuing

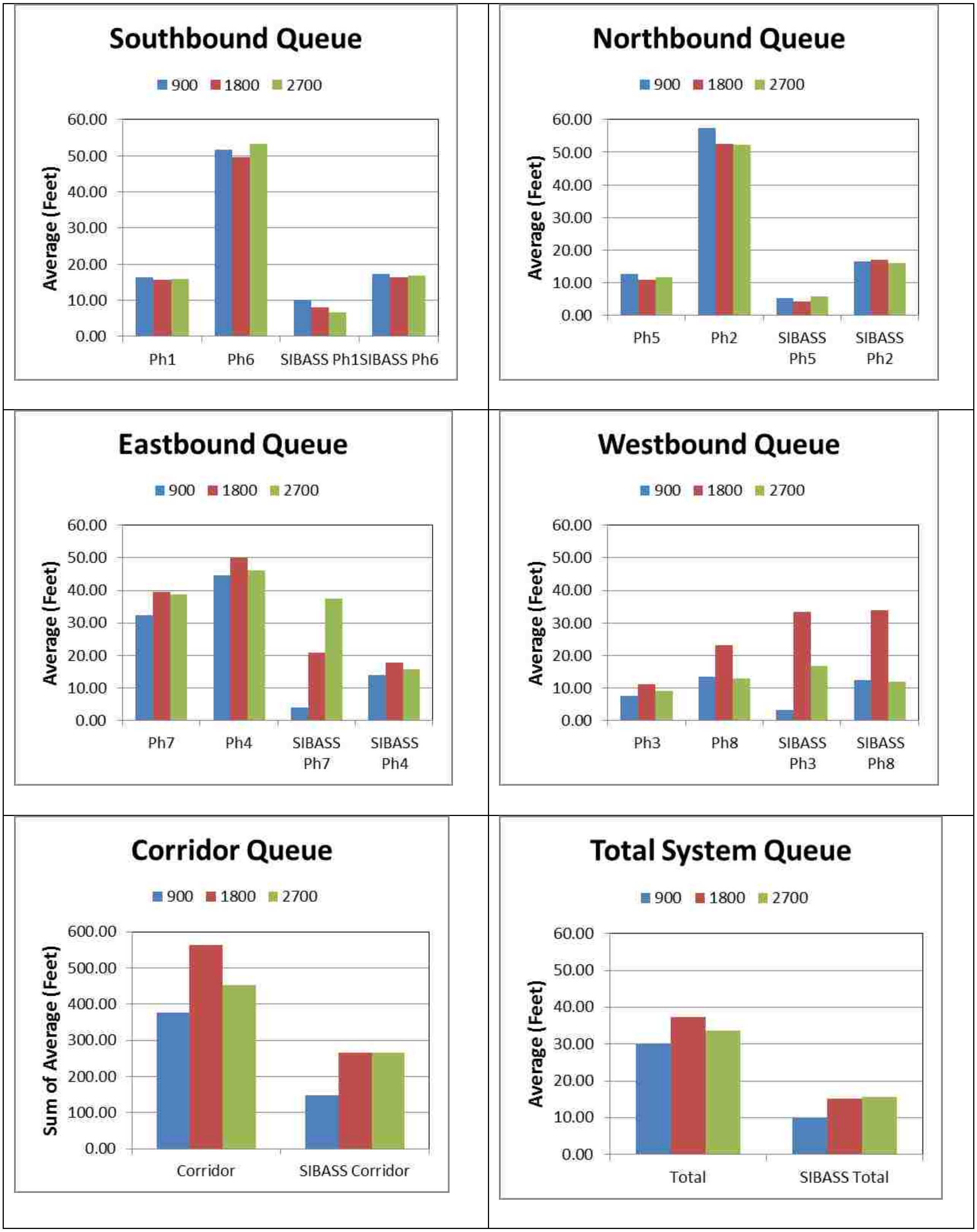


Figure 9-14: Queues by Approach for Corridor Test 3

SIBASS wins against delay optimization in queuing with the exception of westbound queues. The majority of the queuing occurs in the 5 minutes it takes SIBASS to adjust to the new input volume. The delay optimization system has an advantage in that it is already generating green bands along the corridor and incorporating increased westbound traffic into those green bands can be done on the next band, effectively immediately, while SIBASS needs to wait 5 minutes to adjust.

Chapter 10: Conclusions and Future Research Directions

This research has spanned several topics and theoretical implementations. It began with the challenge of developing a new mesoscopic model for implementation into the STATICS evaluation framework. This mesoscopic model needed to be simple enough to implement in Microsoft Excel and yet provide sufficient detail to capture individual vehicle level data such as stops and delay as well as queue lengths. Important signal control parameters such as gap lengths, vehicle presence and intersection and movement saturation also needed to be collectible from the model. Ultimately the STATICS toolkit relies on its built in hybrid queuing model to generate the performance measures necessary to evaluate the performance of the signal control strategies and features incorporated into STATICS.

Work on STATICS also resulted in the creation of a series of adaptive traffic signal control logics based on existing adaptive systems including InSync, ACS Lite and SCATS. These control logics were developed after simulations identified key traffic signal control characteristics for inclusion in STATICS.

The final step in a STATICS evaluation is a cost-benefit analysis. Work for STATICS revealed that public agencies have incredibly poor budget records and fundamentally lack the ability to identify the costs associated with their traffic signal control systems. To begin rectifying this omission, STATICS incorporates a cost-benefit analysis as part of the overall toolkit.

Addressing traffic signal control issues is a major area of future research. Increasing computerization, proliferation of mobile devices, connected vehicle systems and a broadening of transportation scope to include modes of transportation other than the automobile will drive the creation of new traffic signal control systems and optimization methodologies. SIBASS is a new adaptive traffic signal control system designed to operate at the lowest level possible, the individual intersection. SIBASS's design is unique in that it relies on its swarm properties to generate coordination, rather than hierarchical order imposed from a central control.

10.1 Contributions

The STATICS toolkit represents a large step forward in evaluating traffic signal control systems for feature selection and replacement. STATICS is an open evaluation platform in which practitioners and agencies have full access to the operating algorithms and principles. The STATICS system includes a model sufficiently detailed to model the interactions of individual vehicles while maintaining sufficient simplicity to be implemented in Microsoft Excel. STATICS advances the art of traffic signal control evaluation through its ability to set up direct comparisons between varied systems and system features.

The research and development of the SIBASS system and accompanying QACD model has furthered the field of traffic signal control by creating a new model of traffic signal operation, the swarm intelligence model. Swarm intelligence offers many operational improvements compared to more traditional systems. Swarm systems operate at individually simple levels that are generally straightforward to understand as individuals. The defining characteristic of a swarm system, though, takes the design of many individual robots working together one step further. A swarm has properties of its own that exist independently of the individual members. One advantage of swarm intelligence is the ability to optimize different parts of the system independently while using rules that create order through regions or the system as a whole. In SIBASS, the Coordinator and Corridor roles fulfill this duty when the swarm indicates

In the case of SIBASS, the design goal is a traffic signal control system that uses simple rules and optimization criteria to operate an intersection's traffic signal control system. The SIBASS swarm is intended to quickly react and optimize for current traffic conditions. One important byproduct of this optimization process is that the speed of reaction translates into speed of recovery from unexpected conditions making the system more robust to disruption.

The modular nature of SIBASS's network connections means that the swarm will optimize the intersections under its control regardless of the number of intersections involved. The system can accommodate a communications failure to central control simply by becoming two separate swarms separated by the break. This splitting behavior allows the traffic signal control system to continue to operate, albeit in a slightly reduced capacity despite no longer having communications to central control. This is in contrast to the behavior of many systems which fall back to a simpler form of control until communications are restored. With SIBASS, the next phasing and role selection period will reconnect the two swarms when the communications break is restored.

With the inclusion of the Queuing, Acceleration, Cruise and Deceleration (QACD) model, SIBASS can predict intersection performance parameters such as queuing, stops, and delay. SIBASS can then include these predictions in its phase selection and optimization process. In the future, the QACD model will offer an avenue for incorporating connected vehicle data into the traffic signal control process. Currently stochastic methods are used to assign where vehicles will turn and which queues to apportion them to for performance measure calculations.

10.2 Further Research

The STATICS toolkit pushed the limits of complexity that can be implemented in Microsoft Excel. While further advances may be made with STATICS, they will need to be made in a different medium. A revised version of STATICS using the QACD model and improved signal control logic coded as a standalone, open source program could offer significant improvements over the Microsoft Excel version.

There are also significant opportunities to advance the STATICS cost-benefit analysis tools. Currently, the STATICS cost-benefit analysis is relatively simple and only includes the most directly attributable costs. It also offers little guidance on expected values. Further work is warranted to identify the agency and social costs associated with traffic signal control operations.

SIBASS's performance has shown itself to improve corridor performance compared to the conventional and adaptive logics implemented. SIBASS is, however, far from perfect and has many ways it can be improved. Additional consideration is particularly due for the role and phasing selection process. While six roles were proposed in this first version of SIBASS, there is room for the addition of more roles, such as a pedestrian focused role. Transit signal priority is another facet of traffic signal control that should be explored in the context of a role for SIBASS. Additional roles may also consider optimizing based on economic concerns such as cargo value for trucking and number of passengers, among other potential optimization goals.

One surprising area in need of further research is the process of choosing between permitted only, protected/permitted and protected only left turn phases. Particularly when looking at the integration of connected vehicle data into the traffic signal control systems, a number of questions regarding the presence or absence of gaps and the number of left turning vehicles may be answered in real time. This could be an important step toward improving the usage of different left turn phasing restrictions in an adaptive manner.

References

1. Adams, W. F. 1936. Road traffic Considered as a Random Series. Journal of the Institute of Civil Engineers. Volume 4. United Kingdom.
2. Adler, J. L. and V. J. Blue.1998. Toward the design of intelligent traveler information systems. Transportation Research Part C. Vol. 6, Issue 2.
3. Alder, J. L., G. Satapathy, V. Manikonda, B.Bowles and V. J. Blue. 2004. A Multi-agent Approach to Cooperative Traffic Management and Route Guidance. Transportation Research Part B. Vol. 39.
4. Adler, J.L., M. G. McNally. 1994. In-laboratory Experiments to Investigate Driver Behavior Under Advanced Traveler Information Systems. Transportation Research Part C. Vol. 2, Issue 3.
5. Angel, S. and G. M. Hyman. 1970. Urban Velocity Fields. Environment and Planning, Vol. 2.
6. Beni, G. 1988. The Concept of Cellular Robotic Systems. Proceedings of the 3rd IEEE International Symposium on Intelligent Control. Arlington, VA, August 24-26.
7. Beni, G. 2005. From Swarm Intelligence to Swarm Robotics. Lecture Notes in Computer Science. Volume 3342.
8. Blue, V. J., J. L. Adler, G. F. List. 1997. Real-time Multiple Objective Path Search for In-vehicle Route Guidance Systems. Transportation Research Record 1588, TRB, National Research Council, Washington, DC, 1997.

9. Branston, D. M. 1974. Urban Traffic Speeds - I: A Comparison of Proposed Expressions Relating Journey Speed to Distance from a Town Center. Transportation Science. Vol. 8, No. 1.
10. Beimborn, E. A. 1970. A Grid Travel Time Model. Transportation Science, Vol. 4.
11. Bonneson, J. A. and M. D. Fontaine. 2001. NCHRP Report 457: Engineering Study Guide for Evaluating Intersection Improvements. Transportation Research Board – National Research Council. National Academy Press, Washington D.C. 2001.
12. Brownstone, D. and K. Small. 2005. Valuing time and reliability: assessing the evidence from road pricing demonstrations. Transportation Research Part A: Policy and Practice, Vol. 39, No. 4.
13. Cascio, W. 1991. Costing human resources. South-Western Educational Publishing, 1991. http://www.gccaonline.com/eweb/documents/Costing-HR.pdf .
14. Chen, L., May, A., 1987. Traffic Detector Errors and Diagnostics. Transportation Research Record: Journal of the Transportation Research Board, No. 1132. TRB, National Research Council, Washington, D.C., pp. 82–93.
15. Choy, M. C., D. Srinivasan and R. L. Cheu. 2003. Cooperative, Hybrid Agent Architecture for Real-Time Traffic Signal Control. IEEE Transactions on Systems, Man and Cybernetics – Part A: Systems and Human. Vol. 33, Issue 5.
16. Daganzo, C. F. 1994. The cell-transmission model: A Simple Dynamic Representation of Highway Traffic. Transportation Research, Part B. Volume 28, Issue 4.
17. Daganzo, C. F. 1995. The cell-transmission model, Part II: Network Traffic. Transportation Research, Part B. Volume 29, Issue 2.

18. DKS Associates. 2008. Gresham Phase 3 Traffic Signal System Optimization: Adaptive Traffic Signal Control System Benefits Report. Research Report for Federal Highway Administration.

19. Dutta, U., and D. S. McAvoy. 2010. Comparative Performance Evaluation of SCATS and Pre-timed Control Systems. Transportation Research Forum.

20. Economic Research Office. 2013. Moving 12-Month Total Vehicle Miles Traveled. Federal Reserve Bank of St. Louis. St. Louis, MO. 2013. Accessed online at http://research.stlouisfed.org/fred2/series/M12MTVUSM227NFWA

21. Environmental Protection Agency. 2012. Motor Vehicle Emission Simulator (MOVES) User Guide for MOVES 2010b. Environmental Protection Agency.

22. Federal Highway Administration. 2005. Traffic Control Systems Handbook. Federal Highway Administration. Washington, D.C. 2005. (Raw Data) Accessed online at http://www.ops.fhwa.dot.gov/publications/fhwahop06006/fhwa_hop_06_006.pdf

23. Federal Highway Administration. 2008A. Our Nation's Highways: 2008. Federal Highway Administration. Washington, D.C. 2008. (Raw Data) Accessed online at http://www.fhwa.dot.gov/policyinformation/pubs/pl08021/fig2_4.cfm

24. Federal Highway Administration. 2008B. Traffic Signal Timing Manual. Federal Highway Administration. Publication Number: FHWA-HOP-08-024. Accessed online at: http://ops.fhwa.dot.gov/publications/fhwahop08024/fhwa_hop_08_024.pdf

25. Federal Highway Administration. 2011. Our Nation's Highways: 2010. Federal Highway Administration. Washington, D. C. 2011. Accessed online at http://www.fhwa.dot.gov/policyinformation/pubs/hf/pl11028/onh2011.pdf

26. Federal Highway Administration (FHWA). 2012. Model Systems Engineering Documents for Adaptive Signal Control Technology (ASCT) Systems. http://ops.fhwa.dot.gov/publications/fhwahop11027/ . Accessed 3/19/2013. 2013.
27. Fehon, K., and J. Peters. 2010. Adaptive traffic Signals, Comparison and Case Studies. Institute of Transportation Engineers Western ITE Meeting. San Francisco.
28. Floetteroed, G. and K. Nagel. 2005. Some Practical Extensions to the Cell Transmission Model. Proceedings of the 8th International IEEE Conference on Intelligent Transportation Systems. Vienna, Austria. September 13-16, 2005.
29. Fukuda, T. and S. Nakagawa. 1988. Approach to Dynamically Reconfigurable Robotic System. Journal of Intelligent and Robotic Systems. Volume 1.
30. Gartner, N. H., F. J. Pooran, and C. M. Andrews. 2001. Implementation of the OPAC Adaptive Control Strategy in a Traffic Signal Network. 2001 IEEE Intelligent Transportation Systems Conference Proceedings. Oakland, CA, August 25-29, 2001.
31. Gettman. D., S. Shelby, and R. Ghaman. 2006. ACS - Lite Implementation Template. Federal Highway Administration (FHWA). Washington, D.C.
32. Greenshields, B. D. 1935. A study in Highway Capacity. Proceedings of the Highway Research Board, Vol. 14.
33. Hathaway, E. and T. Urbanik. 2012. Memorandum: Task 8 – Tualatin-Sherwood Road SCATS Evaluation. Kittelson and Associates Memorandum on Transportation Operation Innovation & Demonstration Evaluation/Statewide: Task 8 – Tualatin-Sherwood Road SCATS Evaluation.
34. Hathaway, E., T. Urbanik and S. Tsoi. 2012a. Memorandum: Cornell Road InSync System Evaluation. Kittelson and Associates Memorandum on Transportation Operation

Innovation & Demonstration Evaluation/Statewide: Cornell Road InSync System Evaluation.

35. Hathaway, E., S. Tsoi, and T. Urbanik. 2012b. Memorandum: Bend/Redmond SCATS System Evaluation. Kittelson and Associates Memorandum on Transportation Operation Innovation & Demonstration Evaluation/Statewide: Bend/Redmond SCATS System Evaluation.
36. Helbing, D. 1996. Derivation and empirical validation of a refined traffic flow model. Physica A Volume 233.
37. Helbing, D. A. Hennecke, V. Shvetsov, and M. Treiber. 2001. MASTER: macroscopic traffic simulation based on a gas-kinetic, non-local traffic model. Transportation Research Part B. Volume 35.
38. Hunt, P. B., D. I. Robertson, R. D. Bretherton, and M. C. Royle. 1982. The SCOOT On-line Traffic Signal Optimisation Technique. Printerhall Limited, London, England. 1982.
39. Hutton, J., D. Bokenkroger, and M. Meyer. 2010. Evaluation of an Adaptive Traffic Signal System:Route 291 in Lee`s Summit, Missouri. MRI Project 110637, MoDOT Project RI 08-026.
40. Institute of Transportation Engineers. Traffic Signal Timing. ITE Washington, D.C. 2014. Accessed online at http://www.ite.org/signal/index.asp
41. Kendall, D. G. 1953. "Stochastic processes occurring in the theory of queus and their analysis by the method of the imbedded Markov chain". Annals of Mathematical Statistics. Vol. 24. Pp. 338-354.
42. Klar, A., Wegener, R., 1997. Enskog-like kinetic models for vehicular traffic. Journal of Statistical Physics. Volume 87.

43. Koonce, P.. L. Rodegerdts, K. Lee, S. Quayle, S. Beaird, C. Braud, J. Bonneson, P. Tarnoff, and T. Urbanik. 2008. Traffic Signal Timing Manual. Federal Highway Administration. Washington, D.C.

44. Li, Z. 2011. Modeling Arterial Signal Optimization with Enhanced Cell Transmission Formulations. Journal of Transportation Engineering. Volume 137, Issue 7)

45. Lighthill, M. J. and G. B. Whitham. 1955. On Kinematic Waves: II. A Theory of Traffic Flow on Long Crowded Roads. Proceedings of the Royal Society: A229. London.

46. Lowrie, P.R. 1992. SCATS - Sydney Co-ordinated Adaptive Traffic System - A Traffic Responsive Method of Controlling Urban Traffic. Roads and Traffic Authority, Sydney, NSW, Australia.

47. Lyman, D. A. and P. F. Everall.1971. Car Journey Times in London - 1970. RRL Report LR 16, Road Research Laboratory.

48. Mannering, F.L.; W.P. Kilareski, and S.S. Washburn. 2007. Principles of Highway Engineering and Traffic Analysis. John Wiley & Sons. 2007.

49. Martin, T., and A. Stevanovic. 2008. Adaptive Signal Control V: SCATS Evaluation in Park City, UT. Mountain Plains Consortium of the University Transportation Centers Program.

50. May, A., Coifman, B., Cayford, R., Merritt, G., 2004. Automatic Diagnostics of Loop Detectors and the Data Collection System in the Berkeley Highway Lab. California PATH Research Report, UCB-ITS-PRR-2004-13.

51. McTrans (Center for Microcomputers in Transportation). 2013. TRANSYT-7F Webpage. Accessed online at: http://mctrans.ce.ufl.edu/featured/TRANSYT-7F/

52. Metropolis, N. and S. Ulam. 1949. The Monte Carlo Method. Journal of the American Statistical Association, Vol. 44, No. 247.

53. National Electrical Manufacturers Association (NEMA). Traffic Controller Assemblies. Standards Publication No. TS2-1998 v02.04, Washington, D.C., 1998.

54. National Transportation Operations Coalition. 2012. 2012 National Traffic Signal Report Card. Institute of Transportation Engineers. 2012. Accessed online at http://www.ite.org/reportcard/

55. Northwest Signal Supply, Inc. 2009. Voyage Software operating manual Version 3.01.0.

56. Park, B. and H. Qi. 2005. Development and Evaluation of a Procedure for the Calibration of Simulation Models. Transportation Research Record 1934. 208-217. Washington D.C.

57. Paveri-Fontana, S.L. 1975. On Boltzmann-like treatments for traffic flow. A critical review of the basic model and an alternative proposal for dilute traffic analysis. Transportation Research. Volume 9.

58. Payne, H.J. 1971. Models of freeway traffic and control. In: Bekey, G.A. (Ed.), Mathematical Models of Public Systems. 1. Simulation Council. La Jolla, CA.

59. Peters, J. M., J. McCoy, and R. Bertini, 2007. Evaluating an Adaptive Signal Control System in Gresham.

60. Pipes, L. A. 1953. An Operational Analysis of Traffic Dynamics. Journal of Applied Physics, Volume 24 Issue 3.

61. Prigogine, I., Herman, R. 1971. Kinetic Theory of Vehicular Traffic. Elsevier, New York.

62. Planung Transport Verkehr (PTV) AG. 2012. VISSIM 5.40-04 - COM Interface Manual.

63. PTV Group. 2013. PTV Vissim Webpage. Accessed online at: http://vision-traffic.ptvgroup.com/en-us/products/ptv-vissim/

64. Ragland, D., S. Arroyo, S. Shladover, J. Misener, and C.-Y. Chan. 2006. Gap Acceptance for Vehicles Turning Left Across Oncoming Traffic: Implications for Intersection Decision Support. Transportation Research Board 85th Annual Meeting Compendium of Papers CD-ROM.

65. Richards, P.I. 1956. Shock waves on the highway. Operations Research. 1956.

66. Rhythm Engineering. 2013. Rhythm Engineering Website: How InSync Works. Rhythm Engineering. 2013. Accessed online at http://rhythmtraffic.com/how-insync-works/the-insync-model/

67. Roads and Maritime Services of New South Wales. 2013. SCATS. Accessed online at: http://www.scats.com.au/index.html

68. Robertson, D. I. and R. D. Bretherton. 1991. Optimizing Networks of Traffic Signals in Real Time – The SCOOT Method. IEEE Transactions on Vehicular Technology. Vol. 40, Issue 1.

69. Ruskevich, I. 2011. Comparative Analysis of Approaches to Analytical Modelling of Traffic Flows at an Intersection. Transport and Communication, Vol. 12, No. 2. Riga, Latvia. 2011.

70. Selinger. M., and L. Schmidt. 2010. Adaptive traffic control systems in the United States, updated Summary and Comparison. HDR Engineering, Inc.

71. Shelby, S., D. Bullock and D. Gettman. Transition Methods in Traffic Signal Control. Transportation Research Record: Journal of the Transportation Research Board. Volume 1978. 2006.

72. Shively, G., Galopin, M. 2013. An Overview of Benefit-Cost Analysis. Accessed online at http://www.agecon.purdue.edu/staff/shively/COURSES/AGEC406/reviews/bca.htm

73. Siromaskul, S., and M. Selinger. 2010. InSync: The Next Generation of Adaptive Signal Systems.

74. Stevanovic, A. 2010. Adaptive Traffic Control Systems: Domestic and Foreign State of Practice. National Cooperative Highway Research Program (NCHRP) Synthesis 403.

75. Stokols, D., R. Novaco, J. Stokols, and J. Campbell. 1978. Traffic congestion, Type A Behavior, and Stress. Journal of Applied Psychology, Vol. 63(4). American Psychological Society.

76. Texas Transportation Institute and Cambridge Systematics. 2006. Travel Time Reliability: Making It There On Time, All The Time. http://www.ops.fhwa.dot.gov/publications/tt_reliability/ .

77. Transportation Research Board. 2010. HCM 2010: Highway Capacity Manual. National Academy of Sciences, Washington, D.C. 2010.

78. Transportation Research Board. 2000. HCM 2000: Highway Capacity Manual. National Academy of Sciences, Washington, D.C. 2000.

79. Victoria Transportation Policy Institute. Transportation Cost and Benefit Analysis, Second Edition. Victoria Transportation Policy Institute, Victoria, B.C., Canada. 2009.

80. Wang, J., B. Robinson, S. Shelby, B. Cox, and W. Towsend. 2010. Evaluation of ACS Lite Adaptive Control using Sensys Arterial Travel Time Data. Siemens Traffic Solutions, Arcadis, Inc. Sensys Networks Inc. and Fulton County, Georgia.

81. Wapiti Micro Systems Corp. 2011. W4IKS 170 Local Controller software cut sheet http://www.wapitimicrosystems.com/Wapiti%20W4IKS%20Data%20sheet.pdf. Accessed: May 14, 2011.

82. Wardrop, J. G. 1968. Journey Speed and Flow in Central Urban Areas. Traffic Engineering and Control. Vol. 9, No. 11.

83. Wardrop, J. G. 1969. Minimum Cost Paths in Urban Areas. Beiträge zur Theorie des Verkehrsflusses, Universitat (TH) Karlsruhe.

84. Whitham, G.B., 1974. Linear and Non-linear Waves. Wiley, New York.

85. Wiedemann, R. (1974). Simulation des Strassenverkehrsflusses (in German), University Karlsruhe.

86. Wikimedia. "Damping." http://en.wikipedia.org/wiki/Damping. Accessed 3/10/14.

87. Wu, Y.-J., G. Zhang and Y, Wang. 2010. Volume Data Correction for Single-Channel Advance Loop Detectors at Signalized Intersections. Transportation Research Record, Number 2160. Washington, D.C. 2010.

88. Zhang, G., Y. Wang, H. Wei, and P. Yi. 2008. A Feedback-Based Dynamic Tolling Algorithm for High Occupancy Toll (HOT) Lane Operations. Transportation Research Record 2065, 54-63.

89. Zhang, G., S. Yan, and Y. Wang. 2009. Simulation-based Investigation on High Occupancy Toll (HOT) Lane Operations for Washington State Route 167. ASCE Journal of Transportation Engineering. Vol. 35, No. 10, 677-686.